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Final Report

Seismic Discrimination

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LEXINGTON, MASSACHUSETTS

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

SEISMIC DISCRIMINATION

FINAL REPORT
TO THE
DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

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ABSTRACT

This is the Final Report on the Lincoln Laboratory Vela Uniform program. Section I presents an overview of the program from its beginning; summaries of our technical accomplishments for the Fiscal Years 1964 through 1982 are presented in Sec. II. The implementation of the Seismic Data Center is described in Sec. III. A list of publications relevant to our research is supplied in Sec. IV.

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SEISMIC DISCRIMINATION

I. OVERVIEW

A. BEGINNINGS

The almost universal outcry against nuclear testing in the atmosphere reached its peak in the late 1950's, and led to several significant political and technical initiatives. In July 1958, a conference of experts, from both East and West, met in Geneva to discuss the technical verification problems that might accompany a test-ban treaty. The conclusions of this conference (that it would be easy to detect a 1-kt underground explosion at considerable distances) were later criticized extensively, but focused much attention on underground testing and monitoring by seismic means. In December 1958, a U.S. Panel (the Berkner panel) was appointed to study the seismic monitoring of nuclear testing in more detail. In its report, published in June 1959, the panel assessed that current seismic methods were only capable of detecting explosions with yields over 20 kt, and recommended the initiation of an aggressive new program in seismic research into detection and discrimination. In response to this, the VELA UNIFORM program was born, and the responsibility for the program was assigned to the Advanced Research Projects Agency of the Department of Defense.

Initial activities in this program focused on upgrading the existing coverage of seismic stations, and in 1961 the first stations of the World-Wide Standard Seismograph Network (WWSSN) were installed. At the same time, stimulated mainly by research in the U.K., interest in the possibility of using arrays of seismometers was beginning to develop. The U.K. installed a small array in Eskdalemuir in Scotland, and began to develop techniques for processing the data. Several similar arrays were rapidly deployed in the U.S., and similar research began.

Lincoln Laboratory became interested in the VELA UNIFORM program in 1962, since it had developed a substantial expertise in antenna and wave propagation theory. At the instigation of the Director of the Laboratory, a small group was formed in late summer 1962, and asked to explore possible Lincoln participation in this program. The resulting report, presented to the Director in September 1962, advocated a serious Laboratory commitment in this area. This was accepted by the Director and a small startup program was initiated under Lincoln Laboratory's General Research Program in December 1962.

This group began a serious study of the array problem, and participated in the addition of mobile digital-recording equipment to the Tonto Forest array in Arizona. As a result, Lincoln Laboratory was one of the first groups to accomplish digital recording of seismic data. Using these data, and those from other networks, the group began to develop and apply a variety of propagation theory, statistics, and data-processing methods. The group also participated in various DARPA discussions of arrays, and in a joint U.S./U.K. meeting held at Aldermaston, U.K. in June 1963. The subject of array size was a frequent topic at these meetings, and the Lincoln group began to formulate plans for a large U.S. seismic array. This culminated in the submission of a proposal to DARPA in August 1963 to fund an effort to explore the problems that might be encountered by such an array. This proposal was accepted, and the Lincoln VELA UNIFORM program began in October 1963.

B. THE DESIGN AND DEVELOPMENT OF LASA

The Lincoln Laboratory program began slowly, continuing various theoretical studies. However, the political situation was changing very rapidly. The Limited Test Ban Treaty was signed by the U.S., U.K., and U.S.S.R. in August 1963, and this treaty limited all future testing to beneath the surface of the ground. This, in turn, led to a substantial increase in the importance of VELA UNIFORM, and it became the focus of much activity and new funding. As a result, in late summer 1964 the Lincoln program was enlarged and aimed specifically at the immediate development and deployment of a large seismic array.

New staff were assigned to the problem, and by December 1964 a basic design for the array had been completed and construction had begun. The array design consisted of a 525-seismometer array with a 200-km aperture, to be installed near Miles City, Montana. The seismometers were to be arranged in 21 groups (or subarrays), each containing 25 seismometers. AFTAC was assigned responsibility for the installation of the seismometers, and communications from the sensors to the subarray vault. Lincoln Laboratory was assigned responsibility for signal transmission beyond that point, for the construction of an array data analysis center, and for all processing functions at that center.

A site for the Data Center was selected in Billings, Montana, and within a short time (by summer 1965) the seismometers and communications links had been installed, computer equipment had been installed at the Data Center, and testing had begun. The Large-Aperture Seismic Array (LASA) began operations in October 1964, and its technical performance exceeded expectations. Within six months, the experimental period was completed and routine operations were begun.

At this point, Lincoln Laboratory was assigned overall system responsibility for control and maintenance of LASA. Operations and maintenance were handled by subcontract to the Philco Corporation.

C. THE LARGE ARRAY YEARS

With LASA operational, the Lincoln Laboratory program became heavily involved in processing the LASA data, and applying it to the basic problems of detection and discrimination. Initial efforts focused on gaining an understanding of the array data, devising more-and-more complex ways to add the sensor outputs so as to increase signal to noise ratio (SNR), and developing automatic event detection and location capabilities.

The processing of array data was to dominate the Laboratory program for the next six or seven years. Major accomplishments during this period included significant developments in digital time series analysis, the formulation of a frequency-wave number approach to array analysis, the invention of velocity-spectral analysis and the application of sonograms, and a large amount of work in array calibration both for travel times and amplitudes.

A notable accomplishment in this period was the introduction of interactive computer graphics for the analysis of array waveforms. Based on two PDP-7 computers, Lincoln constructed a display system called CONSOLE, which provided an advancement in the state-of-the-art compatibility for the analysis and display of seismic waveforms.

The CONSOLE system was heavily user-oriented. With little preparation, a new user could select a tape containing a given event, play it into the computer, and view the waveforms - all within a few minutes. Facilites were provided for all standard analysis operations (such as filtering, spectral analysis, etc.), and a simple method was provided for users to generate their own FORTRAN programs to manipulate the data. This system attracted visitors from all over the world, and many Ph.D. theses were based on the LASA data and CONSOLE system.

Plans to build a global network of LASAs were already being formulated as it became operational. By 1967, a second array site had been selected in Norway, a subarray was installed, and Lincoln Laboratory was playing an active part in the site evaluation.

However, the array program, while very successful technically, was not nearly as successful for seismic detection and discrimination. The reason that slowly emerged was that the Earth was a lot more complicated than we had suspected. The signals arriving at the various subarrays were much more incoherent than was expected, and this placed a fundamental limitation on the usefulness of the large aperture of the array. The inferred degree of inhomogeneity in the crustal section beneath LASA became the new standard for the way present-day geophysicists think about the continental crust. In addition to variations in signal shape, comparatively large travel-time and amplitude variations across the array were found to be very dependent on source location. As the Norwegian array (NORSAR) began to produce data, all these effects were observed to an even larger degree.

Clearly, array problems needed the services of not only data processors but also geophysicists, if we were to attempt to approach some solutions.

This led to a significant change in the VELA UNIFORM program as a whole, and the Lincoln Laboratory program in particular. Emphasis shifted toward seismological research, and the Laboratory began to hire seismologists into the program.

By 1969, LASA was proven to be an operational entity, and the routine operations were passed into the hands of IBM, leaving the Laboratory free to focus on the data analysis and seismic issues. Realizing that the LASA data were raising questions at the forefront of academic seismology, the Lincoln group responsible for the VELA UNIFORM project was physically moved into new quarters on the M.I.T. campus, where it could closely interact with academia.

The end of the array era was approaching, however, as it became clear that scattering in the Earth provided a natural limitation to the usefulness of arrays. By 1970, interest in array data had diminished considerably, and although LASA was not finally closed down until the mid-1970's, it received little attention in its final years.

D. INTO THE AGE OF GLOBAL NETWORKS

Interest in the overall VELA UNIFORM program seemed to wane as the 1970's began. Movement toward a comprehensive test ban treaty had slowed to a snail's pace, if not stopped all together. However, it was revitalized in 1971, largely as a result of a series of Senate hearings by the Foreign Relations Subcommittee on Disarmament. Several influential senators spoke strongly for an expansion of the U.S. seismic discrimination program.

Since the large array program had not proven as successful as had been hoped, the program returned to an earlier idea, namely the use of a global distribution of single stations. Such a network, especially if equipped with low noise sensitive instruments, would lead to a substantial improvement in detection capability and, by providing wide azimuthal coverage, would allow more sophisticated studies of the source mechanism of seismic events. Plans were begun for a new borehole digital seismic station, which later became known as the Seismic Research Observatory (SRO).

At Lincoln Laboratory in the early 1970's, the VELA UNIFORM program was becoming more and more oriented toward geophysical problems. By this time most of the staff in the program were professional seismologists, and research was focused on improving our understanding of earthquake source mechanisms and path effects.

When the new emphasis on global networks became apparent, the Laboratory organized an international project to clarify the detection capability of existing seismic stations. With excellent cooperation from many countries, the seismic records for one month (20 February to 19 March 1972) were carefully analyzed and the results sent to Lincoln Laboratory, where they were checked and assembled into a list of events. The results of the International Seismic Month (ISM) project were surprising. Existing organizations producing global lists of earthquakes were able to identify about 300 events per month. The ISM event list contained 1000 events, and clearly showed that detection capability was a strong function of the care used in reading and analyzing the seismic records.

The ISM project was a time-consuming task. Many of the records supplied were reread by Lincoln seismic analysts, in order to obtain a consistent data set. In addition, a new data-base management and display system was devised to allow interactive analysis of the parameter data set. The project was completed in 1974.

1974 was an important year in that a Threshold Test Ban Treaty was negotiated and signed by the U.S. and the U.S.S.R. Immediately, the VELA UNIFORM project became heavily interested in yield estimation. Part of the Lincoln Laboratory program was diverted into this area, and focused on the estimation of, and bias in, body-wave magnitude m_b. However, following the signing of the Threshold Test Ban Treaty, there was a protracted set of negotiations between the U.S. and the U.S.S.R. to resolve the problems raised by peaceful nuclear explosions. Though this matter was finally settled in 1976, it was clear that sentiment in Congress was not in favor of the treaty, and it was never submitted for ratification. The VELA UNIFORM program again appeared to lose the interest of political leaders, and plans were announced that the entire program would be phased out over the next three years.

E. THE SEISMIC DATA CENTER

When the Carter administration came into power in 1977, the test-ban treaty situation changed completely. The Threshold Test Ban Treaty and the Peaceful Nuclear Explosions Treaty were set aside, and new negotiations were initiated, aimed at formulating a Comprehensive Test Ban Treaty. Early in these negotiations it became clear that a key element in any potential treaty would be the deployment of sensitive seismic stations within the national boundaries of both the U.S. and the U.S.S.R. This raised two new issues that strongly influenced the Lincoln Laboratory program.

First, the concept of internal stations raised the question of detection and identification at local and regional distances (out to, say, 2000 km). In the past, this distance range had been largely ignored for discrimination purposes, because the observed waveforms are complicated by crust and upper-mantle structure. Lincoln Laboratory carried out a number of investigations in this area, but results were limited by the scarcity of adequate data in this distance range.

Second, the possibility that internal stations might send continuous, densely sampled, seismic data raised a number of data management issues. Until this time, the only existing system for handling digital data in an operational way was at the Seismic Data Analysis Center (SDAC), in Alexandria, Virginia. However, the SDAC facility did not have the capacity to handle the anticipated new data flow.

For several years, Lincoln Laboratory had been involved in discussions and planning concerning updating the SDAC system. The treaty developments therefore led DARPA to ask Lincoln to formulate the design of an entirely new state-of-the-art system that would be capable of fulfilling whatever requirements that might be specified in the final treaty. This had a major impact on the Lincoln Laboratory program. Research in seismology was substantially reduced, computer scientists were brought into the program, and the main focus of the program became computer hardware and software systems, and data-base management.

The design for the new Seismic Data Center (SDC) was completed in September 1979. After much discussion, the design was centered on a hardware configuration consisting of multiple minicomputers interconnected by a local computer network. This allowed for flexibility, in order to respond to changing requirements, and reliability by including redundant computers for critical functions. The design was accepted by DARPA as the basis for further development.

At this point, the Laboratory was asked to assume the task of constructing a prototype system which would allow the testing out of the design concepts. This prototype phase, including hardware acquisition and software development, took about two years, and the prototype system was completed in September 1981. According to the original plans, Lincoln would then have embarked on a two-year development phase during which the prototype would have received extensive testing and performance evaluation, and the system would have been optimized for all the tasks that it would be required to perform in an operational context. However, these plans were cut short by further political developments.

When the Reagan administration took office in 1981, movement toward a Comprehensive Test Ban Treaty slowed substantially. This left in doubt one of the main initial motivations for the project. However, two other motivations had arisen, and the SDC was now aimed at these new functions.

The first of these arose from the discussions of the U.N. Committee on Disarmament. Instigated primarily by Sweden, this Committee had established a Group of Seismic Experts to look in detail at the possibility of an international test-ban treaty monitoring scheme. Over several years, this group had formulated a plan for international data-exchange between participating countries, and were beginning to engage in data exchange experiments. This placed a requirement on the U.S. to install an operational International Data Center so that the U.S. could participate in the experiments.

The second motivation was related to the seismological research community. Since the installation of the first SRO station in the mid-1970's, the number of digital seismic stations around the world had been increasing steadily. However, the existing mechanisms for acquiring the new high-quality digital data were primitive. A clear need had arisen for a central data center that would store these data in an accessible form.

In response to these two motivations, DARPA decided to establish a prototype operationsal SDC immediately. The hardware and software at Lincoln were moved to a new site in Rosslyn, Virginia, where development is now continuing. This new facility is known as the Center for Seismic Studies. At the same time, the Lincoln Laboratory VELA UNIFORM program was placed in a phase-out mode, in which it was reduced to zero by the end of FY 1982.

During its twenty-year existence, the Lincoln program not only made major contributions to the field of seismic discrimination and seismic data management and analysis, but also counted some of the foremost seismologists in the country on its staff.

II. TECHNICAL ACCOMPLISHMENTS

A. FISCAL YEAR 1964

During this period, the bulk of the group's effort involved processing of recorded seismic data from the four stations of the Weston Network in New England and from the Vela arrays at TFO (Tonto Forest Observatory, Payson, Arizona) and CPO (Cumberland Plateau Observatory, McMinnville, Tennessee). The Weston data arrived in real time by FM telephone line and were recorded on multi-track FM tape. Data from TFO and CPO were originally in the form of dubbed 14-track FM tape recordings provided by the Seismic Data Laboratory (Alexandria, Virginia), who also supplied a number of analog and digital recordings made at other locations. Later, five channels of TFO data were received by telephone line, and equipment was ordered to record up to 81 channels directly in digital format at TFO. Computer programs were written for the two machines available, an IBM 7094 and the TX-2 (a Lincoln-built machine that proved very useful for our work, partly because of the flexible display and input-output facilities).

A number of investigations in seismic data processing progressed. Efforts were made to build up a set of the following types of displays for each of a number of events: (1) the usual seismometer output functions of time along three perpendicular axes; (2) displays of polarization of "particle motion" as a function of time; (3) power vs frequency and time ("Sonograms"); and (4) running plots of $C(\alpha)$, power as a function of vector arrival velocity. In addition, we gained practical experience in reading and interpreting seismograms from the Weston Network. In addition to studies of actual seismic data, we pursued the application of communication theory ideas to arrays (Refs. 1-4). Theoretical work, previously begun, on solution of the elastic wave equations for continuously stratified media was continued. Our chief interest was in understanding the nature of the P-waveform and its relation to the source.

One of our greatest concerns involved testing certain large-array ideas on the "Extended TFO" configuration and participating in the planning of a several-hundred-kilometer large-aperture array having several hundred sensors.

Several conclusions emerged from our investigations:

(1) The coherence between signals from the sensors spaced up to several hundred kilometers is quite high, particularly for the first 5 to 10 seconds.

(2) A network of four stations such as the Weston Network can provide, from simple calculations on arrival times, epicenter information on magnitude 5.0 to 6.0 events, whose rms accuracy is about 1° in azimuth and about 3° in epicentral distance.

(3) A single three-component station can provide epicenter information on most events in the magnitude 4.5 to 6.0 range of 4° rms accuracy in azimuth and 15° in epicentral distance.

(4) Automating the selection of events from preselected epicentral regions seems perfectly feasible by either method.

(5) The highest frequency at which useful signal energy is present for the magnitude and distance ranges appropriate to the discrimination problem is about 3.5 Hz. The lowest useful frequency is currently unknown and awaits more data on shear- and surface-wave phases from weak teleseisms.

(6) The usefulness of sonogram, particle motion, and $C(\alpha)$ displays for diagnosing seismic phases had yet to be determined.

(7) Small single multicomponent seismometers providing large outputs from masses on the order of grams are feasible.

B. FISCAL YEAR 1965

1. July 1 to December 31, 1964

During this period, a large fraction of the group's effort went into planning and initial implementation of the Large-Aperture Seismic Array (LASA), a 200-km 525-sensor array for nuclear test surveillance then being installed in Montana (Refs. 5,14,23,25-27). Lincoln Laboratory was responsible for telemetry and signal processing and display. Acceleration of the LASA program necessitated the recent addition of a number of people to the Lincoln VELA UNIFORM effort. Until this occurred, some of our more basic investigations had to be curtailed - for example, those dealing with unusual signal displays.

However, work on network processing for rapid on-line epicenter location in large arrays proceeded steadily, and some new theoretical and experimental results in array processing were obtained.

Much of the instrumentation was completed for the study of certain large-aperture array problems by processing signals recorded at the TFO. This instrumentation allowed recording in standard digital format of up to 81 sensors within the TFO site itself or from outlying mobile stations, and it also permitted daily screening of observed seismic activity so that only the recorded data from time periods of interest had to be saved.

Work on the use of processed output signals to discriminate seismic source type was limited to an analysis of how best to combine the results of applying a number of separate discriminant criteria. The following conclusions were drawn from this work.

(a) Automatic on-line detection of presence or absence of a moderately large seismic event was feasible. Automating a system of event detection followed by measurement of arrival times at stations in a network appeared promising.

(b) Use of such time-of-arrival measurements for rapid machine location of epicenters was feasible, thus allowing one to decide soon after a given event whether or not the data were interesting enough to save.

(c) Digital recording of large numbers of sensors, some remotely telemetered, can be done quite conveniently, and screening of the events avoids an excessive accumulation of data tapes.

(d) Maximum-likelihood array processing turns out to have a very simple physical interpretation, and when tried on small arrays gave the predicted signal-to-noise improvement.

(e) The estimation of noise spectral density in frequency-wave-number space will provide useful information when carried out within existing large arrays, and its analysis points to certain optimum array geometries.

(f) The feasibility of a particular scheme of digital-data transmission over voice-bandwidth telephone circuits at rates around 8000 bps has been demonstrated indirectly by sending a fraction of that rate over a corresponding fraction of voice bandwidth.

These results are all relevant to large seismometer array structures such as the LASA.

2. January 1 to June 30, 1965

During this period, virtually all efforts were directed toward the realization of the LASA. The main foreseeable function of this array was to improve the SNR and signal-to-reverberation ratio of real teleseismic events so that existing notions for source discrimination and for studying the physics of the Earth may be more widely and reliably applied.

The engineering of the LASA array was formulated in detail, particularly with regard to the signal transmission and on-site processing capabilities. Initially, the on-site signal-processing capability was quite modest, but was expected to expand rapidly. Various array-processing investigations continued at the Laboratory (Refs. 28,29,30,32). (Some of these already involved a small flow of data from LASA sensors.) Upon completion of the LASA installation, these techniques were to be applied to evaluate, off-line, the performance of the LASA concept and to choose and optimize the procedures to be programmed permanently into on-site signal-processing equipment.

Successful operation of the array, either for scientific data gathering or nuclear test surveillance, requires delayed and slowed-down processing of digital recordings which must be limited as much as possible to times of interesting seismic activity. For this reason, automatic detection and location of events was under very active investigation (Refs. 16,25,26).

Work on the discrimination problem, on three-component arrays, and on unusual signal displays was somewhat inactive during this period. Data-gathering operations at TFO were completed and our involvement with this operation terminated.

C. FISCAL YEAR 1966

1. July 1 to December 31, 1965

During this period, the experimental LASA in Montana was put into operation and was used for an extensive program of routine monitoring and data recording. Most of the physical elements of the system were working more reliably than had been anticipated, considering the size of the system, the speed with which it was built, and the inaccessibility of some portions of it.

An extensive program of research and experimentation with various array-processing techniques was under way using LASA data. Off-line SNR gains of 30 dB (1.5 mag.) were typically obtainable. These gains appeared to be more a consequence of the use of large numbers of sensors and complex processing, and less a consequence of the large aperture. Predetection processing gain for on-line detection and location of very weak teleseisms was not completely evaluated, but appeared certain to be smaller than the 30-dB off-line figure.

Studies of automatic event screening investigations would soon reach the point at which the various capabilities of the experimental LASA could be well established, the signal-processing hardware design finalized, and a design of a possible global network of LASAs worked out, should it be needed.

The large array was not an end in itself but a signal improvement system whose outputs were useful for both nuclear test monitoring and for research on the solid Earth. We now began to use LASA data for both of these purposes.

Two miscellaneous studies of seismic instrumentation were completed: a survey of electromagnetic means of measuring long-baseline Earth strains, and a comparative critique of the noise performance of several methods of amplifying near DC signals.

2. January 1 to June 30, 1966

During this reporting period, we continued to study the engineering performance of the experimental LASA in Montana and concluded that, in any future such installation, no redesign of the system would be necessary, although improved methods of automatic fault monitoring would be required.

Data from the experimental LASA were analyzed for the purpose of establishing its various capabilities (Refs. 29,33). It was found that above magnitude 3.5, 50 percent of all events lying from 30° to 90° from the station were detected using the present on-line beam processing having a 12-dB SNR gain. Off-line procedures with gains up to 27 dB are achievable with the present LASA. The effect of SNR improvement, expressed as an equivalent shift in seismic magnitude of the received signal, was found to be about the same as that given by the SNR gain for some waveform features, but greater than that for others.

A study was made of P-complexity using a new computation procedure intended to take advantage of coda differences between subarrays. A new technique for testing the calibration of both amplitude and phase of a seismometer across its entire operating band using a single input signal, a pseudorandom square wave, was developed. An analog processing system for a three-component single sensor was built and used to accumulate data on the particle motion of a number of teleseisms.

In order to deduce the effect of changing any of a number of parameters in the LASA seismometer and its associated signal transmission circuitry, a mathematical model embodying these elements was set up on the computer.

D. FISCAL YEAR 1967

1. July 1 to December 31, 1966

Beginning in this period, we attempted to shift the main focus of our work away from the LASA as an end in itself toward consideration of the seismic surveillance problem as a whole and the role that networks of arrays of various kinds might play in this function.

Studies of networks were then limited to mathematical simulations and to studies of LASA data as sample outputs from a station to a net of stations. The particularly interesting outputs are various waveform discriminants, which were being studied in detail. We investigated the on-site detection and location that take place autonomously at a single large-array station. These detections and locations, performed at one such station, can be used to initiate off-line array-processing functions at this and other stations. A variety of off-line processes, using both short- and long-period array structures, were tested. The development of techniques for automatic maintenance and monitoring of all physical elements of large arrays progressed satisfactorily.

2. January 1 to June 30, 1967

During this period, considerable attention was given to preparations for a possible second large-array station, then anticipated to be located in Norway. A tentative rough system design was worked out, based on Montana experience, and a seismic survey of the area was planned which would provide suitable corrections to the initial design (Ref. 51). Analytical studies of seismic networks embodying several large arrays continued.

In the area of discrimination techniques, the principal new result involved studies of body- and surface-wave magnitude differential. On a large number of blasts and earthquakes, complete separation occurred. At this time, this discriminant was usable down to body-wave magnitude 4.7 for Central Asia; below this level, surface waves were not detectable in Montana.

Developments in the on-line detection and location of events in large array structures off-line array processing of both long- and short-period signals continued (Refs. 40,41,45).

E. FISCAL YEAR 1968

1. July 1 to December 31, 1967

During this period, work was more or less completed on identification techniques using data from the long-period (LP) portion of the Montana LASA as it now stands (Ref. 62). Emphasis shifted toward improving short-period (SP) capability so that the virtually complete separation of blasts and earthquakes afforded by LP data (above magnitude m_b=4.5 to 5) could be extended to lower magnitudes at which surface waves are undetected, but above the SP detection threshold (3.5) (Ref. 52). We continued to develop the ability to locate epicenters from a single LASA by beamsplitting, an important part of the identification procedure, particularly for small-magnitude events invisible at other stations.

The first SP subarray of a projected large array in Norway was partly completed, preliminary signal and noise analyses made, and a design study made of the LP portion of the array.

The application to a variety of geophysical problems of digital recording and automatic and semiautomatic computer processing was under continued investigation and refinement. During this period, progress was made in greatly improving the convenience of signal-handling operations through the use of a seismic data analysis console, a small general-purpose machine with appropriate hardware and software for real-time man-machine-data interaction.

Seismological research work in the program involved a continuation of effort on problems of Earth structure and the nature of the microseismic noise (Refs. 53,61) as well as a new one, the measurement of Earth strains over several kilometer atmospheric paths using laser interferometers (Ref. 64).

2. January 1 to June 30, 1968

Identification studies using SP and LP small and large arrays continued. Means were developed for applying the available simple waveform discriminant parameters to large numbers of events with a high degree of automaticity; to aid the search for new discriminants, a set of signal-processing tools which provide a detailed dissection of individual events was developed.

Work on detection and location at single stations proceeded in several directions. LASA detection and two methods of LASA location were studied using data recorded during the Kuriles ocean-bottom seismic experiment of late 1966. A new processing method for high-resolution space-frequency analysis of signals or noise was developed; using this and other tools, a study of Montana LP noise was completed (Ref. 72). Studies of signal and noise properties of the Norway large array (NORSAR) site continued. A survey of work elsewhere on signal-to-noise improvement by seismometer emplacement in deep boreholes was made.

F. FISCAL YEAR 1969

1. July 1 to December 31, 1968

A large data base of parameter measurements on many earthquakes and presumed explosions was generated and subjected to previously available explosion-earthquake discriminants, such as LP surface-wave and SP spectral-ratio measurements (Refs. 63,66). By using this data base, several parallel efforts to improve SP discrimination beyond that available from spectral ratio alone were made (Ref. 52). These approaches, which offered a modest improvement in decreasing the SP identification threshold, involved the use of dominant period, detailed examination of spectral behavior as a function of source type and magnitude, and application of pattern classification algorithms.

In an attempt to understand the use of P-complexity (ratio of P-coda to P) as a source discriminant, detailed directional analysis of several events showed that the coda has the same direction of approach as P, within the resolving power of the LASA. A possible explanation of the high-complexity values from certain regions was formulated.

Use of data from the initial NORSAR installation was extended to surface-wave discrimination studies. The observed different behavior of the western U.S. and Central Asia areas suggested an attempted explanation in terms of basic differences in tectonic type of the two regions.

Recent changes in the group's physical facilities included a move to closer proximity to the Department of Geology and Geophysics at M.I.T., and improvements in processing hardware and software. The question of seismic detectability of missile launches was studied.

2. January 1 to June 30, 1969

We continued to devote attention to short-period P-wave spectral characteristics as a promising avenue for decreasing the present identification threshold. Recent work, concentrating on studies of the Q-factor (losslessness) of the mantle near the LASA (Montana) and NORSAR P-waves was developed and tested and a theoretical model of explosion sources was used to infer mantle Q for NORSAR. NORSAR and Montana P-spectra of the same earthquakes were used to compare the mantle Q for the two locations.

A systematic examination has been made of the usefulness of a continental array consisting of coherently combined seismometers spread over an aperture of several thousand kilometers (Ref. 74). The hoped-for improvements in depth phase detectability and in resolution of the directional properties of the arriving P-coda were not realized, presumably due to large intersite differences in crustal structure which proved impossible to equalize.

The usefulness of the surface-wave vs body-wave (M_s vs m_b) discriminant depends on good knowledge of the surface-wave arrival time, particularly when other events may interfere. A brief study of the reliability of arrival-time observations of LASA was completed.

An analysis was completed of the probability, as a function of magnitude, of successfully applying either or both of two discriminants at LASA, M_s vs m_b and spectral ratio. This information is required for system studies of the identification problem.

The derivation of a seismicity recurrence curve from a large data population and its interpretation in terms of detection threshold were analyzed as a parameter estimation problem. We carved out several experiments in discerning migrational trends in successive earthquake epicenters using computer-generated movies.

The laser interfermometer strain measurement project yielded interesting new information on atmospheric fluctuations.

G. FISCAL YEAR 1970

1. July 1 to December 31, 1969

The Laboratory continued its studies on discriminants, with emphasis on the simultaneous utilization of data from several scattered sites. Cepstral analysis methods were applied to four Soviet presumed underground explosions as recorded at Norway, LASA, and three United Kingdom array sites. Reflections from the Earth's surface above the shot points may have been detected. The same data were used to detect changes as a function of yield in SP spectra which were consistent with those predicted by theory for explosions. LRSM data from stations in North America were used for a preliminary test of a discriminant based on body-wave magnitude, period, and the minimum complexity observed for the set of stations utilized. A limited study of depth determination using possible depth phases at LASA and NORSAR was completed. Utilization of two or more stations reduces the probability of erroneously locating an explosion at depth based on apparent depth phases.

Investigation of discrimination based upon surface- and body-wave magnitude (M_s-m_b) continued with emphasis upon the regional effects due to both receiver and source locations. A study of western United States events using LRSM data verified that presumed explosions and earthquakes tend to be separated by M_s-m_b but that the two populations are close together. Additional M_s-m_b data for Asia were measured at Norway and compared with similar LASA data. A tentative interpretation of Kurile Islands data in terms of a downthrusting lithosphere was undertaken, and preliminary analysis indicated that this would be useful for regionalization studies.

Some studies of explosion characteristics at ultra-long periods were undertaken. Frequency-wave-number analyses of data from Nevada Test Site (NTS) shots recorded at LASA were computed in the frequency range from 0.01 to 0.05 Hz (Ref. 73). Significant coherent signals were not detected at about 0.02 Hz but were detected at lower frequencies. Spectra were also obtained for teleseismic explosions detected by ultra-long-period instruments operated by the M.I.T. Earth and Planetary Sciences Department at Harvard, Massachusetts.

Array-processing research included studies of continental-sized arrays and data equalization for array processing (Ref. 74). Continental array beamforming was modified to compensate for variations in signal power in time and at different sites. Equalization filters for LASA were investigated as a preliminary to studies of deconvolution filters which might be used to improve secondary-phase detection.

Previously developed tools were applied to problems of geophysical interest. The potential value of LASA and array method for studies of core phases was demonstrated. The high-resolution frequency-wave-number method was applied to micro-barograph data.

2. January 1 to June 30, 1970

Work was now completed on the nature of the seismic signal from events in the Soviet Union at a known test site. In order to put further factual basis behind the SP spectral discriminants we used, comparisons were made between theoretical models of explosions and spectral characteristics across a range of magnitude from 5.4 to 6.1 (Ref. 76). Although many features seem predictable, lateral variations in attenuation in the mantle are substantial and need careful allowance for any predictive scheme for signal character. Studies of NTS events were pursued in two directions. The survey of ultra-long-period spectral characteristics was completed, and the remarkable notch in the coherency of the signal at 0.02 Hz continued to show itself. There appeared to be continued promise in SP spectral discrimination, so a collection of regional observations of NTS events was made for this purpose.

A large amount of research was devoted to the problem of seismic observations in a laterally heterogeneous Earth. The evidence on such heterogeneities was growing steadily and was frequently connected with aspects of plate tectonics. It was demonstrated that severe alterations in signal shape can be the consequence of underthrust lithospheric slabs, as clearly revealed by our study of Longshot. We re-examined the role of complexity in such a situation and found that its value as a discriminant may be higher than previously thought. The LASA bulletin was now produced automatically and it was a matter of some interest to know whether the location process was affected seriously by these heterogeneities which could affect $dT/d\Delta$ observations at LASA. Preliminary results showed that much of the scatter in location in some areas could be attributed to near-source structure (Ref. 70). High-quality array data also allowed us to begin to understand gross heterogeneities in absorption of seismic waves. A study of spectral characteristics of seismic signals revealed such variations in Q. A major study of the composition of the Rayleigh-wave signal in terms of direction of approach and delay time was completed and showed striking multipath propagation which may be attributed to continental margin and mid-ocean ridge effects (Refs. 86,97,98). Analysis of surface waves for discrimination needs some indication of the potential amplitude variations these phenomena imply; for this reason, and also to study wave propagation in the vicinity of underthrust plates, a general-purpose ray-tracing program was developed and the first results from this were shown (Ref. 78).

Attention was given to aspects of array processing which could be exploited where single seismometers are of no use. In particular, we looked at coherence in signal and its implications. Even underground explosions seemed to be somewhat incoherent across the array, and it is fairly clear that this incoherence was not entirely attributable to sub-LASA structure, since it was possible to find extremely coherent earthquakes (Ref. 77). The power of VESPA (a display of energy in incident angle time space) at picking up small signals in the P-wave coda was strikingly demonstrated in terms of reflections from upper-mantle discontinuities. Studies continued on the ability of VESPA to deal with multiple signals from different events (Ref. 100).

Further analysis of the frequency-wave-number spectral estimation used in many of our studies led to exact probability distributions for the estimators. A study of the relative merits of the maximum entropy, maximum likelihood, and conventional methods of power spectral density estimation was completed.

The console analysis facilities were substantially upgraded to allow the study of a much larger set of data than previously (Ref. 101). In addition, programs which are central to routine analysis of seismic data were steadily being made available on the PDP-7 computers for immediate use to avoid the time-consuming need to process much of our data at the M.I.T. Computation Center. With the arrival of more NORSAR data and the acquisition of a large amount of worldwide standard network film material, we intended to broaden the basis of our discrimination techniques.

H. FISCAL YEAR 1971

1. July 1 to December 31, 1970

We completed several investigations involving the spectral analysis of surface-wave data from explosions at the NTS. A wide range of explosions was analyzed in order to see if spectral characteristics vary with magnitude and if standard models of the explosive source adequately describe the radiation at long periods. A large composite diagram of all the data allowed comparison with theoretical predictions. A discussion of energy partitioning was given and it was concluded that less than 1 percent of the available elastic energy at long periods goes into surface waves. In another study, SP observations of explosions from seismic rays which have been reflected off the inner core were examined. These signals were slightly encumbered by interfering signals and the source characteristics that they suggest were unusual, calling for pulses of equal and opposite polarity 2 s apart. A multi-array study of Eastern Kazakh events of a range of magnitude and the calculation of experimental transfer functions from the data allowed us to compare different explosive source models. We also noted that there was a marked difference in signal character from array to array, indicating some considerable variability in radiation characteristics for different directions.

We carried out several studies on the propagation path. Use of the high-resolution technique for analysis of surface waves having a 40-s period demonstrated multipath phenomena almost as complex as earlier studies at higher frequencies had revealed (Ref. 98). It was again possible to associate these multipath signals with reflections from continental margins and tectonic features. In addition to multipath Rayleigh waves, it was possible to find very-long-period body waves in the coda. Many of these were identified as of the general type $(PS)_n$, where n is of the order of six. The ray-tracing program, described briefly in the previous Semiannual Summary (Ref. 75), was now being used to explore the implications of lateral inhomogeneities in the Earth. In particular, realistic models for underthrust plates were used and the powerful effect of inhomogeneities in producing shadows and high-amplitude regions were obvious. P-waves from two earthquakes practically at the same location and PcP from the same events recorded at LASA were displayed side by side to reveal the effect that the Aleutian's plate has on introducing disturbances into the waveform of P-waves. A Chinese event raised some important questions for discrimination and these were discussed with respect to P-wave propagation in the Earth. The event appeared to have a very clear depth phase, pP, associated with it. It, however, would be classed as a possible explosion by the $M_s:m_b$ criterion. Insights into the upper-mantle structure beneath China can be drawn from this event and are important for discrimination. An unusual opportunity to make a direct measurement of the Earth's Q was possible with the installation of near-shot seismometers for the nuclear test Boxcar. Teleseismic observations of the signal at NORSAR were combined with the near-source observations to obtain a mean Q for the path of about 2000 (Ref. 104).

In the area of array-processing research, we applied recent developments in the spectraforming method of processing partially coherent seismic data. Thus far, it was clearly demonstrated that averaged spectral information from selected sensors in LASA was greatly superior to the spectra of a time-domain beam from the same sensors. In particular, high frequencies were very well preserved by spectraforming. On the other hand, the signal-to-noise improvement of time-domain beamforming was not available to the spectraform. We examined this method with particular reference to the use of higher frequencies for discrimination. Another study considered the capabilities of a new estimator of the energy density spectrum. This estimator used noise statistics and was able to yield a SNR gain of 3 to 9 dB over the conventional spectraform process. A study was completed of the ability of LASA to detect signals in the presence of interfering signals. In particular, Rayleigh waves from one event were searched for in the main wavetrain and the coda of another event. The long duration of the coda frequently made it the dominant feature in masking events, so coda statistics were also gathered. It was concluded that a signal 6 dB below the interfering signal could be correctly identified. The opportunity at LASA to sample a larger portion of the seismic wave field than an individual seismic station can enabled us to look very carefully at what seismological statements, particularly with regard to amplitude, are tenable. A study of P and PcP amplitudes was made and showed the extent of scatter and how much of this was attributable to source structure. It was concluded that the PcP/P ratio is a difficult figure to extract from individual observations.

2. January 1 to June 30, 1971

During this period our work was mainly, but by no means exclusively tied to the effective use of large arrays. Until this time, we predominantly considered LASA in our publications; however, with the recent completion of the Alaskan Long-Period Array (ALPA) and NORSAR, intensive study of these two arrays in the coming year was anticipated.

Since the general acceptance of the M_s:m_b technique as a means of discriminating between earthquakes and explosions, the seismological community has devoted considerable time to answering the following questions:

(a) Can the threshold at which this discriminant works be lowered by improved global instrumentation?

(b) Is there a sound scientific basis for discrimination and does this predict a size of event below which conventional seismic techniques will see no distinctions?

(c) Can the determinations of M_s and m_b be made more reliable, particularly at low magnitudes, or at least can the reason for the frequent large scatter in values be well understood?

(d) Are there any further discriminants which might work to a lower threshold or supplant M_s:m_b in certain cases?

We used LASA in extending previous studies of the spectral characteristics of earthquakes and explosions in the western U.S. The total spectrum (both SP and LP) was now available for analysis. It was also possible to calculate the integrated spectrum in these two bands. Comparisons were made between the Rayleigh-wave energy and the P-wave energy for explosions and earthquakes in order to see to what degree the energy is partitioned. Preliminary results showed that there is separation, although not by an entirely satisfactory amount without some restrictions on window lengths and spectral bands.

The strange nature of inner-core reflections of NTS explosions was considered further, with an attempt to fit a source time function of an explosion to the pulse shape. We concluded that the ground displacement in the vicinity of the source had a very strong impulsive component, and that the "width" of the impulse was about 2 s for a 1-Mton explosion. If the near-source displacement behavior of all explosions is dominantly an impulse, the basis for discrimination would lie in the spectral differences between impulses and steps - more characteristic of earthquakes.

A suit of earthquakes in the Kuriles region revealed a striking distinction between two practically parallel and widely separated sets of events using the M_s:m_b technique. Neither population overlaps with any possible explosion line, but we had a unique opportunity to attempt to find what differs between the two earthquake types. It was concluded that the dimensions of the earthquakes control the separation through the duration of the event and consequent spectral effects.

A study of explosion BOXCAR as recorded at NORSAR was made in order to fit the P-wave shape to theoretical explosion and propagation characteristics. A high degree of similarity can be obtained using a Haskell model of the explosive source and a value for t* (the attenuation parameter) of 0.5.

Attempts to explain the nature of the P-wave amplitude variation associated with explosion Longshot now proved successful (Ref. 107). The three-dimensional ray-tracing program and the observations of high- and low-amplitude signals in various regions assumed to be due to focusing and defocusing were brought together, in conjunction with geophysically reasonable model of the Aleutian arc, to yield good agreement. The influence of upper-mantle structure on the estimate of m_b is profound.

The multipath studies of Rayleigh waves reported in previous SATS reports were extended to Love waves and it was demonstrated that the same general sources of multipathing occur in both cases, namely internal reflections from continental margins (Ref. 98). Striking similarity was found between Love and Rayleigh waves and it was demonstrated that the same general sources of multipathing occur in both cases, namely internal reflections from continental margins. Striking similarity was found between

Love and Rayleigh multipathing for some events, but there were some for which the two wave types seem to undergo different reflections.

Short-period seismic waves from presumed explosions in different regions of the Soviet Union had remarkably different codas. We identified events from two regions in which the coherency of the coda was very different. A coherent coda can be explained in terms of near-source structure, such as horizontal layering, while an incoherent coda, it seems, must be ascribed to some sort of scattering process. This process cannot be under LASA, so we concluded that it must take place in the mantle beneath the Soviet Union. It is important for two reasons - one is that magnitude estimates should take account of energy content within the coda, and the other is that we may have in coherency a very interesting geophysical observation on the microstructure of the Upper Mantle.

Determination of the nature of the signal reflected and transmitted at a boundary for which properties vary over a distance comparable to a wavelength has importance in any attempt to use P-wave signals to understand source characteristics. New time-domain solutions were formulated for simple models in which both velocity and density may vary smoothly through the boundary.

On the basis of the first data to be received from NORSAR we were able to estimate the travel-time anomalies associated with that array. The most notable thing to emerge so was the strong correlation of the azimuthal error (arising from fitting a plane wave to the incoming signal) with the tectonic region.

Further results of spectraforming were obtained. NORSAR (which was particularly suitable for this process) revealed a number of events in Iran which have particularly strong high-frequency content. These events were being considered in detail.

We examined the significance levels that may be associated with Vespagram and Beamsplit displays. Definitions of a seismic "signal" and "noise" were formulated within the context of the complicated output that these programs present to an analyst. An example of a P-wave signal undergoing a complicated reflection at a sloping continental shelf was used to illustrate the significance levels.

The crustal transfer function ratio of Phinney was used in an effort to extract crustal parameters from LASA data. Vertical and horizontal LP instruments at many subarrays were used and a clear trend was found for the period of the function's peak, indicating a general thinning of the crust in a westerly direction.

Peculiar very-long-period signals from LASA have been reported in the past, and there was some question of their reality. Further analysis revealed the strong possibility that these signals arise from intermodulation distortion when a SP Rg phase travels across the array.

We continued to improve our data-analysis facilities. A high-grade printer-plotter was now available to either PDP-7 computer for hard-copy output.

The Lincoln daily bulletin continued to be produced from visual observation of LASA data. Its capabilities were described in the previous SATS (Ref. 79). It was available on a routine basis to those who may need quick information about seismic events.

I. FISCAL YEAR 1972

1. July 1 to December 31, 1971

Until this date, our work was predominantly centered on the most-effective use of LASA, the large aperture seismic array in Montana. Our interests were now broadening into the use of two recently completed arrays, NORSAR and ALPA, the WWSSN, and new LP instruments. We continued to pursue research on the phenomenology of the seismic source and on several features of wave propagation.

LASA and NORSAR were both used to study explosions in order to try and improve our understanding of teleseismic aspects of the explosive source. P-waves at NORSAR from Nevada explosions for a wide range of yields and burial depths were studied in order to attempt to isolate effects arising from the primary pulse, the surface reflection (pP), and the spalling or slap-down that occurs shortly afterward. Very clear contributions from each of these phenomena could be isolated. This study was corroborated by studies of core phases from Cannikin and Milrow in the Aleutians, from which similar conclusions emerge. It was further possible to begin to obtain an unencumbered view of the source, and remarkably short durations for earthquakes were measured. These convert into sizes for events of less than 10 km even up to m_b 6.0.

In recent years, large computers allowed new approaches to problems in wave propagation. One such approximate technique handled inhomogeneous regions at a relatively low expenditure of computing time. We studied this technique to establish its usefulness in comparison with an exact method.

From this work, some insight was gained into the extent of inhomogeneity necessary before approximate techniques lose their value. It is now widely accepted that many regions of the Upper Mantle contain presently active or fossil slabs. As a continuing study of the effect these inhomogeneities have on seismic propagation, we examined the effect that slabs have on the spectral content of body-wave signals. The result was difficulty in distinguishing slab effects from anelastic attenuation.

Noise studies were under way for NORSAR and ALPA. Long-period noise at NORSAR had the expected constituent coming from the Atlantic Ocean, but also a significant component appears to originate to the east of NORSAR. Such noise, which is in the same sector as Eurasia, may need some careful attention in discriminating small events. Joint ALPA/LASA noise studies revealed sources of ocean-generated microseisms which are close to regions of low pressure as reported on weather maps. Long-period signals at NORSAR were being collected for the purpose of studying variations in character of the surface-wave train with event location. In addition to these variations, it was possible to identify portions of the array which are less sensitive to the important shorter-period continental phase. First array-processing results were retained for NORSAR discrimination purposes. Beamforming and matched-filter techniques appeared to be working well, and it would soon be possible to establish a surface-wave threshold for NORSAR; this figure will probably be seasonally dependent. LASA corrections for core phase arrivals at individual subarrays were now included in our standard Lincoln-based programs, and were proving valuable in improved processing capabilities.

With the availability of NORSAR and ALPA data, it was desirable to consider these arrays not only in isolation but in terms of a continent-wide network for discrimination. For this purpose, two new projects were initiated. A search was carried out to identify the most efficient means of creating a bulletin using arrays as well as single stations. Thus far, use of the LASA detection log in conjunction with a smaller number of WWSSN stations proved a powerful means of obtaining a much larger earthquake catalogue. Capabilities of the long-period constituent of the WWSSN for discrimination were being assessed with a view to studying the larger population we expected to have available shortly.

At this time, we received data from the Block-Moore seismometer installed near San Diego. We carried out noise and signal analysis and concluded that the best SNR at this site was in the 0.03- to 0.05-Hz band. It was also possible to generate imitation WWSSN records from these data in order to obtain an understanding of the degradation that too broad a filter has on the detectability level of surface waves. The relation between nonpropagating seismic noise and microbarograph output was studied at LASA. We concluded that correlation techniques enable nonpropagating noise to be significantly reduced.

The large amount of data now available in our Lincoln facility was being documented for access by a program called LISTAR. This program, based on the remote-console-accessed Lincoln IBM 360 computer, would enable us to generate lists of events of interest within minutes, and have full information on how to find relevant data. The Analysis Console was the subject of a movie designed to demonstrate its capabilities; it was also featured in a BBC television production on solid Earth geophysics.

Finally, LASA was used to demonstrate for the first time the presence of seismic phase PKJKP, and hence the rigidity of the inner core (Ref. 105).

This issue was in doubt for 35 years, but it now seems possible to assign a shear velocity of 2.95 $\pm$ 0.1 km/s to the inner core. Furthermore, LASA was being used to study the fine structure on the boundary of the inner core.

2. January 1 to June 30, 1972

A study was made of some unusual events in Asia which fail, or almost fail, the M_s:m_b discriminant. These constitute a small but not negligible proportion of events in that region (Ref. 110). One event caused particular difficulty, with an apparent depth phase but every other aspect of an explosion. A catalogue of presumed explosions in the Soviet Union away from the regular test sites was assembled. A time-domain analysis of seismograms from a large Siberian earthquake was made. This event had special interest, being in a region of only mild seismicity. Certain features in the deconvolved record suggested that rupture dimensions and velocity could be extracted from the suite of records. The question of the cause of discrimination was reopened with an examination of conclusions that can be drawn from earthquakes of apparently very small dimensions which discriminate with ease. We concluded that the partition of energy between P-waves and Rayleigh waves may be the central cause. A study was completed of R_g phases from cratering and fully contained explosions in Nevada. We found that explosions that break surface are richer in R_g than fully contained events.

Extensive work was done at Lincoln on the multipathing of Rayleigh waves, and now a ray-tracing program was used on a globe with continent/ocean distinctions (Ref. 78). The results showed striking agreement with observation, and opened up the possibility that we could more adequately predict expected surface-wave magnitudes from hypothetical sources on a real Earth. Travel-time studies up to the present had to make assumptions about near-source heterogeneities which may not be valid. We therefore conducted a P-wave travel-time study which used only deep-focus earthquakes. A rather surprising result emerged. Rays which have penetrated the deepest mantle showed very systematic deviations from standard travel-time tables of up to +1 s. This result was of interest in characterizing regions of the deep mantle and also in attempts to predict the value of seismic observatories at distances beyond 90°. A cognate result was found from recent array studies of $dT/d\Delta$ and azimuth anomalies. It appeared inevitable that there are large- and small-scale lateral variations of significant amplitude throughout the whole mantle, but particularly near the core-mantle boundary.

Work continued on describing the structure beneath LASA, in terms of a Chernov-type approach in which the amplitude and phase fluctuations observed at individual seismomoeters were related by a model in which the earth beneath LASA is a randomly varying medium with small interfaces such as the sediment/basement boundary (Ref. 131). A routine technique was proposed for quality control of LASA, or any other digital seismic data, by use of pseudorandom input to the calibration coil and spectral analysis of the resulting output tape.

The increasing availability of NORSAR data and the interchange of scientists with the NORSAR data center led to an increasing amount of research into NORSAR capabilities. Studies of NORSAR signal amplitudes had concentrated on the degree of coherence in SP data across the array, and contrasts were made with amplitude scatter at LASA. We found that NORSAR body-wave magnitudes of seismic events were generally lower than global averages. A possible reason for this in terms of near-surface high-impedance values was proposed. The false-alarm rate in the NORSAR detection processor was analyzed and some unexpected features in it were explained in terms of spectral characteristics of signals. Noise spectra for LASA and NORSAR SP data were contrasted, and we asserted that no effort should be made to filter out the NORSAR high-frequency signal in favor of 1-Hz energy.

A detailed study was completed of LP nonpropagating noise (Ref. 122). This largely had its origin in microbarographic fluctuations. The theory of the effect of these fluctuations on the surface of the Earth needed some care, as previous models tended to ignore terms in integrals which do not converge. The collocation of ALPA and a LP seismometer of Pomeroy type at Fairbanks, Alaska allowed us to start an evaluation of the relative merits of instruments recording in somewhat different frequency bands. A population of overlapping time intervals was being examined.

Results of the pilot study on SP network capability were examined, and the importance of using LASA's detection log in conjunction with some carefully selected WWSSN stations was emphasized. Early prospects were considered from the International Seismic Month for which Lincoln Laboratory had acted as host. This project involved the collaboration of several groups around the world with access to large quantities of seismic data. A bulletin based on short-period P-wave readings for a 1-month period in early 1972 was issued shortly after, and, in the second phase, surface waves would be analyzed. We then hoped to reach useful conclusions on the contributions that can be made by individual stations to a seismic monitoring network.

J. FISCAL YEAR 1973

1. July 1 to December 31, 1972

NORSAR had now been in full operation for more than a year and we devoted considerable effort to studying its short-period P-wave characteristics. These included a greater degree of incoherence and amplitude fluctuation from site to site than was observed at LASA. Our first concern was to accumulate a sufficient body of data to see whether there were any clear patterns to these fluctuations. It seemed at first sight that there were not. Evidence was found that sources relatively close to one another have substantially different amplitude patterns across NORSAR. We foresaw that an important effort in the near future would be an attempt to determine the extent to which fluctuations could be modeled in a geophysically satisfying way. Many seismic source regions are within 30° of NORSAR, and accurate location of these required a good understanding of the $dT/d\Delta$ curve in this range. This was the distance range, however, for which we expected the most variability owing to crustal and upper-mantle lateral heterogeneity. We assembled newly measured $dT/d\Delta$ values in this range and remarked on the similarity of the curve to that for western North America.

Work was in progress on the time delays within subarrays at NORSAR. This was to consider the problem of whether beaming within individual subarrays needed to be more sophisticated than a simple plane-wave approach.

Collaboration with the scientific staff of NORSAR continued at a high level. The most recent visitor to NORSAR, Mr. Sheppard, was now in the process of compiling an extensive set of time corrections for subarrays of

NORSAR. This would be important for two reasons: (1) it would contribute to the refinement of locations with NORSAR, and (2) it would enable us to search for the sort of propagation anomalies which were found at LASA and associated with heterogeneity in the middle and deep mantles.

If anisotropy in elastic properties exists in the crust and upper mantle - a frequent conjecture as yet only sparsely documented - it might be possible to use an array to look at surface-wave velocity variability as a function of azimuth. A search was made for anisotropy both at LASA and NORSAR, but the results thus far emphasized the very serious problem of separating anisotropy from heterogeneity both within the array and beyond it. Frequency dependence of the approach angle of Rayleigh waves to LASA is associated with continental complexity to the west of the array.

An attempt was made to invert the large data set of ($dT/d\Delta$, Azimuth) data collected from individual subarrays at LASA by placing a highly corrugated interface at depth. This surface cannot be ascribed to any particular depth beneath the array, but if it were associated with the Moho it could be mapped out in an approximate form.

An alternative approach to the problem of interpreting this data set is to treat the scatter in the data as being indicative of a medium with scattering properties describable by a Chernov-type model. This technique has shown how certain parameters of a random medium could be inferred from the data (Ref. 130). Further, the impact of a random element on seismic array techniques for event location was examined. Some events at LASA appeared more coherent than others, and in one paricular case of an incoherent event we were able to identify two separate P-waves arriving simultaneously at the array from substantially divergent directions. We believe that this multipathing evidence, rather similar to that obtained some time ago for Rayleigh waves, may lead us to further interpretation of the middle mantle as a laterally heterogeneous medium. Work advanced on an extensive travel-time survey of the mantle using deep-focus earthquakes. It was possible to map some regions of the mantle, particularly near the core boundary, which have seismic velocities differing significantly from the mean. A study was completed of the contribution of S-waves to the coda of a P-arrival. It was possible to infer a structure (probably at the sediment-hard rock interface) which could generate such P-S converted energy.

A survey of focal mechanisms of Eurasian earthquakes was started. This, it was hoped, would give us a clearer understanding of the events against which we have to discriminate in that region. It may also assist us in the explananation of so-called "anomalous" events which fail the $M_s:m_b$ discriminant. Our initial results highlighted the extraordinary diversity of mechanisms away from well-defined boundaries. A special study was completed of a large Persian earthquake for which parameters such as stress drop dimensions, and slip could be inferred. Also completed were the statistics of a major earthquake swarm for which many singular properties had been noted. Comparison was made of the energy release time profile with recent work of Knopoff on stochastic seismicity. A deep-focus earthquake in the Hindu Kush region was examined for its rather unusual suppression of the depth phase pP. Without this phase, there would be grounds for suspicion over this event, but the LP phase sP helps to confirm the network-determined depth. Further examination of a Siberian earthquake by means of time-domain analysis of WWSSN seismograms was carried out.

Work on the correlation between microbarographic and LP seismic noise was completed. It was possible to suppress seismic noise by several decibels with cross-correlation techniques, but doing this on a routine basis required continued re-evaluation of cross-correlation functions as the coupling between atmosphere and ground is dependent on wind speed and direction. Burial of instruments at 200 m may be, in the long run, a more economical way of suppressing this noise. The question of optimal monitoring of surface waves at distances of less than 20° was under consideration. We studied the signal and noise characteristics at LASA when explosions at NTS are observed. At this distance (12°), the SNR appears relatively constant from 12 to 20 s.

Work on the ISM continued to progress (Ref. 116). At this time, we examined in great detail the detection logs of the LASA and NORSAR arrays in conjunction with all other single-station data in order to look for credible events to add to our present bulletin. Substantial interactive computer aid was now provided by a new system called DADS (Data Analysis and Display System) modeled on our experience with the display console.

Finally, two more general seismological studies were performed in the Laboratory in the last six months. A study of core reflections PcP showed the constraints within which core/mantle boundary models must lie. Work on free oscillation showed the value of using the focal mechanism of an earthquake in extracting spectral peaks. Comparison of peaks from the Alaskan and Colombian quakes showed systematic and significant divergences which probably have to be associated with mantle heterogeneity.

2. January 1 to June 30, 1973

For the previous 18 months, we concentrated attention on the capability of deployed seismic instruments during a period in February-March 1972 known as the International Seismic Month (ISM).

The Norwegian array, NORSAR, continued to be the subject of much of our attention. The puzzling complexity of short-period P-wave observations across the array was further examined, and order appeared to be emerging from some of the complicated recordings of Eastern Kazakh events. First results of an "array diagram" approach to NORSAR's mislocation anomalies were obtained and they showed features very similar to those observed at LASA. Multipath observations of surface waves were being examined - the location of NORSAR may make it less vulnerable to multipathing.

We continued to have a strong interest in the effects of heterogeneity in the Earth on seismic signals. A model of the crust and upper mantle in the western United States was used for a continental region based on LASA's surface-wave reporting ability. Further evidence for lateral heterogeneity deep within the earth was obtained. Multipathed body waves were observed from an event 95° distant from LASA, and an amplitude anomaly found for events in the Pacific recorded at LASA. In both cases, some sort of heterogeneity was necessary in the middle or deep mantle to explain the observed phenomena.

We devoted an increased amount of our effort to problems of evasion and counterevasion. Two specific evasive techniques were considered: multiple shots, and hide-in-earthquake. Seismograms were synthesized to give an idea of what would be needed to mimic complexity and polarity reversals of the depth phase. A seismogram which distorts the $M_s:m_b$ relationship was investigated as well as possible countermeasures. Experiments on array detectability of body waves in the coda of a large earthquake were beginning to give us some quantitative feel for the amount of time that signal masking is possible.

A study of PcP was completed (Refs. 123,136). An unusual feature of this work was the inability to reconcile results from deep and shallow earthquakes; it was shown that some fundamental difference in propagation losses exists between P and PcP for travel in the upper mantle; P-S conversion may be at least partially responsible for this.

K. FISCAL YEAR 1974

1. July 1 to December 31, 1973

A major effort of the group at this time was to study the detection and location capability of the existing network of seismic stations and arrays. The period 20 February to 19 March 1972 was designated as the International Seismic Month (ISM) and, with the excellent cooperation of seismologists in many countries, the available seismic data for this period were analyzed in detail. The first phase of this project consisted of the preparation of an epicenter list based on the SP arrivals at selected WWSSN stations, Canadian network stations, and a number of arrays including LASA and NORSAR. This phase was now completed, and the final epicenter list contained 996 entries. Special attention was given to the precision of the estimates of epicentral location, focal depth, and magnitude, and the events were categorized by the reliability of these estimates. The second phase of the study concerned the association of LP arrivals with the listed events, and the assignment of surface-wave magnitudes. The problem of associating the LP and SP data raised a number of interesting questions that are important for seismic discrimination. This phase would be completed shortly. The final report on this study, including basic statistical analyses of the data, would be available in the spring of 1974.

We continued to have a strong interest in research concerning the performance of seismic arrays, and a number of studies of this kind are described. We have developed the comparison of NORSAR with LASA, and it became apparent that much of the observed complexity of SP arrivals at NORSAR may be attributed to crust and upper-mantle structure. Several studies were completed detailing the nature of this complexity for each subarray, in terms of spectral characteristics, and explaining how these influence the performance of the array as a whole, in terms of array diagrams. Some of these features were similar to those found at LASA.

Research in seismic discrimination concentrated on two subjects - the interfering Rayleigh-wave problem, and the further study of the depth phase pP. The presence of multipathing can complicate the process of the separation of Rayleigh waves from two events, but recent results indicated some success using high-resolution frequency-wave-number techniques. Complications in the structure of pP due to reflections at internal boundaries in the Earth were demonstrated, and the identification of pP in explosion records explored.

In preparation for making use of the global seismic information to be available via the ARPA Network, we extended our research into global seismology, and strengthened our facilities for the rapid access and processing of digital data. Improvements in world-wide seismic station corrections had been proposed, and we continued our study of inhomogeneities in the Earth. S-wave travel-time anomalies showed evidence of these inhomogeneities even more clearly than P-waves. In addition, we carried out a study that was the first step in a series of investigations attempting to relate earthquake source mechanisms to large-scale tectonics.

Our development of a sophisticated interactive computer facility for utilizing the capabilities of the ARPA Network continued. We would have a permanent connection into the network in the very near future, and we expected to be ready to receive seismic information as it became available on the Network.

2. January 1 to June 30, 1974

A major achievement during the current research period was the completion of the basic compilation of seismic data from the ISM. These results were published in the form of two Lincoln Laboratory Technical Notes (1974-14 and 1974-15) (Refs. 127,128). The event list formed an ideal data base for a variety of studies in seismic discrimination, and the experience gained during the study was expected to have a significant impact on any future operational monitoring scheme.

We became heavily involved in the design of the data management system that will accompany the new seismic instrumentation currently being deployed by the DARPA Nuclear Monitoring Research Office (NMRO). Our basic charge was to ensure that the acquisition, flow, and storage of these new digital data met the requirements of those groups actively engaged in studies related to seismic discrimination. A related aspect of this work involved the exploitation of the full power of the computational facilities of the ARPANET for the storage, transmittal, and retrieval of both seismic data and the associated network documentation. Development of these systems was still in an early stage.

With the completion of the bulk of the data analysis associated with the ISM, we embarked on a series of investigations into the mechanism and focal depth of the seismic source. We had shown that average M_s-m_b and moment-M_s relationships place bounds on acceptable theories for the spectral characteristics of the seismic source. Information about these relationships can be deduced from frequency-magnitude curves. Other studies were concerned with the effects of upper-mantle structure on focal mechanism solutions, and the determination of the source dimensions for earthquakes in a localized geographical region.

Investigations into the determination of the focal depth of seismic events were proceeding in several directions. It was demonstrated that maximum-entropy spectral analysis may be applied to the identification of depth phases by the location of cepstral peaks. This method appeared promising. Another study continued our analysis of the estimation of focal depth from surface-wave spectra. It was shown that certain Earth structures that were consistent with observed surface-wave dispersion curves can lead to very inaccurate depth estimates. It was not yet clear that this method has any useful application to the seismic discrimination problem, particularly at low magnitudes.

Our studies of the effects of Earth structure and path variations continued, and were concerned with both surface and body waves. We achieved further success in predicting the refraction and multipathing of Rayleigh waves by lateral variations in crustal structure. Using body waves, we completed a refined version of the amplitude-distance curve, and investigated the nature of precursors to pP, S, and SKS from certain deep-focus events. Two other studies examined body-wave scattering - one as upper-mantle structure affects PcP/P amplitude ratios (Refs. 128,136), and the other as crustal inhomogeneities affect the P-wave coda at short distances.

Finally, we completed three investigations that are continuations of earlier work. Our study of the tectonics of Asia included a detailed analysis of a Baikal Rift Zone earthquake; we extended our analysis of NORSAR travel-time anomalies into aseismic regions, and applied the single-channel event detector described previously.

We were developing a sophisticated interactive computer facility as an in-house research capability that would enable us to access and manipulate seismic data once they became available on the ARPANET. Progress in the design of the appropriate software was continuing.

L. FISCAL YEAR 1975

1. July 1 to December 31, 1974

Research into topics directly related to seismic discrimination and evasion was concentrated on two areas. First, some new approaches to the determination of surface-wave magnitude were explored. It was shown that useful information about the shape of the group velocity curve could be deduced directly from the seismogram, and this led to a much more satisfactory path correction than those commonly employed. Second, we were exploring multivariate techniques that would enable a much more complete parametric representation of the seismogram to be applied to the problems of discrimination between different source mechanisms, and an approach to the multiple-shot evasion problem.

A number of studies of methods for the determination of focal depth were carried out. Very promising results were obtained for the identification of the surface reflection pP from explosions using maximum-entropy cepstral analysis. This technique has the potential for becoming a powerful tool in any seismic monitoring scheme. Continued study of the effect of depth on surface-wave spectra showed a strong influence of crustal structure, enough to make the method somewhat suspect. Application of measurements of S-P times was examined, and, although the method is potentially powerful, there is clearly considerable difficulty in identifying the S-arrival in many instances. Another study attempts to model the characteristics of the proposed DARPA seismic network. It was shown that this network will have some difficulty in resolving accurate focal depths for many events in Eurasia.

We continued our work on the development of a management structure for data and information from the proposed DARPA seismic network. Application of the On-Line System (NLS), developed by Stanford Research Institute, appeared promising, and experiments in the storage and retrieval of information via the ARPANET were carried out. Other network studies included a continuation of our effort during the ISM, with emphasis on the characteristics of a

32-station network. With careful data analysis, it appears that such a network is almost as good as the whole set of ISM stations for the production of a global earthquake bulletin.

Our studies of the nature of inhomogeneity in the Earth were becoming heavily involved in scattering processes, particularly in the mantle. Several investigations indicated that these processes may play a dominant role in the absorption and conversion of energy in SP body waves. The presence of anisotropy in the scattering medium was postulated, and shown to constitute a potentially important effect.

In the field of seismic source mechanisms, we completed several studies aimed at the interpretation of source parameters from observation of LP body and surface waves. One study indicated the possibility of determining gross source characteristics from long-period P-waves. Another formulated a method for the estimation of source parameters from the amplitude and phase spectra of surface waves from pairs of earthquakes.

We also initiated a study of the time variation of seismic activity, hoping to clarify problems related to network detection and hide-in-earthquake evasion. Evidence was obtained that the level of global seismic activity shows rapid fluctuations in level that were largely independent of magnitude. Viewed as a time series, the activity variations appear to contain some significant periodicities, though the cause of these has yet to be established.

In anticipation that digital seismic data soon will be available in quantity on the ARPANET, we continued to develop a facility to enable us to access and manipulate these data. We were now in the process of developing the necessary software, and we anticipated being able to access this new information source when it became available.

2. January 1 to June 30, 1975

Several investigations in the general area of seismic body waves were carried out. We continued to develop the application of maximum-entropy cepstral analysis to the detection of pP-phases for explosions. Delay times estimated by this method agreed very well with published shot depths and surface accelerogram recordings. An attempt was made to verify seismic reciprocity for SP earthquake data, as a background to the problem of calibration of aseismic areas in a threshold test treaty situation. Results were encouraging, but a residual amplitude variation by a factor of 2 (0.3 m_b units) remained unexplained. In another study, a new improved method for the calculation of ellipticity corrections was described.

In the area of surface-wave studies, we extended previous work on surface-wave propagation in Eurasia. We obtained the first results from an extensive attempt to use existing crustal-structure information to predict surface-wave path refraction and multipathing effects. Some large deviations were predicted. In another study, the source mechanisms of some Hindu Kush earthquakes were estimated from the joint analysis of spectra from earthquake pairs. An earth flattening correction for Rayleigh-wave dispersion at long periods was developed from normal mode theory, and seemed applicable to a wide variety of structures. Another interesting development from free oscillation theory was the possibility of representing surface-wave sources in a moment-tensor formalism. This would appear to be advantageous for seismic discrimination problems. A new approach to the estimation of path corrections for surface-wave magnitudes was tested using data for the Cannikin explosion. Only limited improvement over existing techniques was demonstrated so far.

Earlier work on the determination of seismic-source parameters from long- and short-period P-waveforms continued. Considerable success was obtained using LP information, and it was clear that there is considerable source information in the SP waveforms, though propagation effects make it hard to extract in some cases. An interesting application of source mechanism discrimination by a multi-parameter approach was tested. Earthquakes on the mid-Atlantic ridge can be separated into dip-slip (ridge) and strike-slip (transform) types with a high level of success.

Research into Earth heterogeneity and path effects concentrated on two areas - the inversion of P-wave travel-time residuals to obtain lateral variations in structure, and the further study of the scattering of seismic waves. The first results from a global analysis of 728,072 observations of P and PKIKP were obtained. Third-order spherical harmonic analysis indicated significant correlations between inhomogeneities at different levels in the mantle. Inversion of travel-time observations at NORSAR showed evidence of pipe-like structures that extend below the Mohorovicic discontinuity (Ref. 154). Polarization studies of the SP arrivals at the three-component site at LASA showed a surprisingly complex coda which was a strong function of source location. The locations of the scatterers were being investigated. A theoretical study of primary scattering by a transition zone of changing velocity was outlined. New attempts to characterize the scattering process beneath large arrays were being carried out.

We continued investigations into the properties of earthquake time series, formed by counts of earthquakes above a given magnitude threshold per unit time. Significant correlations between the time series for widely separated regions of various tectonic types were found. This strongly suggested the presence of a global earthquake-triggering mechanism. Spectral analysis was applied to the regional earthquake time series, using the maximum-entropy method, and approximately 30 percent of the energy in the spectrum was found to correlate across all regions. A spectral peak at a 6-month period is presumably due to Earth tides. Another at 7.6 months remains unexplained (Ref. 148).

We were deeply involved in the design and development of the data management system for the proposed ARPA seismic network. In particular, we were experimenting with a documentation system for the network, based on the NLS developed by Stanford Research Institute. Creation of file structures and input of documentation were progressing. An attempt to access filed information on the datacomputer was successful.

We continued to update and modify our in-house computer systems so that we could take full advantage of the new digital seismic data as they became available on the datacomputer.

M. FISCAL YEARS 1976 AND 1976T

1. July 1, 1975 to March 31, 1976

A detailed investigation into the problems associated with the estimation of magnitude by a network of seismic stations was initiated. This was prompted by some earlier studies which suggested that the effects of station detection thresholds may be to insert a positive bias into network magnitudes for small events. The problem is primarily a statistical one, and a series of statistical models were developed in order to facilitate the removal of these effects. The next important problem was the optimum determination of the parameters describing the detection characteristics and bias of each station in the network. Some preliminary results along these lines were obtained. Other studies in magnitude estimation concentrated on existing bulletin data, and several investigations showed that then current methods of determining magnitude, particulaly body-wave magnitude m_b, were open to some criticism.

We continued to attack the general problem of Earth structure and heterogeneity. An inversion of free oscillation data to obtain the attenuation parameter Q showed rather low values of Q in both upper and lower mantles, and no evidence for a frequency dependence of Q. Earlier work on tracing the paths of Rayleigh waves across the Eurasian continent was extended by the inclusion of more information on crustal structure. Severe deviatons from great-circle paths and large amplitude anomalies were predicted, and the agreement with observation was good. Studies of the P-wave codes from Novaya Zemlya explosions, using wave-number analysis and adaptive deconvolution, showed complex arrivals generated in the vicinity of the source. Other studies involved reflections from the 600-km discontinuity, and the applications of spatial correlation and transmission holography to seismic data.

Further investigations of the maximum-entropy method of spectral analysis focused on the determination of the order of a time series, and the optimization of the length of the prediction error filter. Application of the method to the network determination of focal depth was formulated. Effects of source geometry on the discrimination between events with different source mechanisms were being studied. A series of travel-time tables based on a parametric representation was assembled. These have the advantages of high accuracy and low computer-storage requirements. An analysis has been completed which links the concept of the moment tensor of an earthquake with its radiated energy. An application of normal mode theory led to a new method for the calculation of the permanent displacement fields of an earthquake.

We continued to develop the software and systems necessary for the analysis of digital seismic data from a global network. We adapted previous software into a form suitable for the display and processing of SRO data. An interactive system, utilizing the IBM 370/168 at Lincoln Laboratory, was designed for the comparison of observed waveforms with those predicted by source mechanism theory. We continued to update the seismic documentation files that we constructed using the NLS system. Also, we were developing the additional software necessary to the full utilization of our connection to the ARPANET and the datacomputer at the Computer Corporation of America.

2. April 1 to September 30, 1976

We engaged in a series of related projects, all aimed at improving our understanding of body-wave magnitude m_b, a quantity of considerable importance for teleseismic yield estimation. In particular, we focused our attention on the various kinds of bias that can affect single-station and network measurements of m_b for an event. One study reduced the large volume of magnitude data contained in the ISC Bulletin, in order to obtain values of station bias for a set of 72 stations. The resulting biases showed good correlation with tectonic region, particularly in the U.S. At the same time, the results of this study indicated disturbing nonuniformity in operator performance at a number of stations (Ref. 168).

Earlier work on attempting to remove m_b bias due to detection characteristics continued. We began a series of numerical simulations which would allow us to examine the contributions of the various different parameters, including seismicity models and instrument saturation. At the same time, we were developing various methods for the estimation of these parameters. The use of magnitudes measured with respect to a reference station appeared particularly promising. Related studies were concerned with removing the bias that can arise from a combination of the shape of the source spectrum, attenuation in the Earth, and instrument response. The traditional method of dividing the observed amplitude by the dominant period of the signal is only a naive approach to a complex problem. Indications were given that it would be possible to make a much more sophisticated approach to the removal of these effects.

Improvements to previous Lincoln Laboratory work on the use of ray-tracing techniques to study the propagation of surface waves from sources in Eurasia were made. Lateral heterogeneity within the oceanic lithosphere was included by utilizing the known variation of phase velocity with age. Other surface-wave studies included an application of the seismic moment tensor formalism to the analysis of earthquake source mechanism. As an example, the Fallon earthquake data were utilized.

We concentrated our efforts in the area of evasion techniques on the problem of the separation of the signals from a closely spaced sequence of shots. The utilization of maximum-entropy cepstral analysis appeared, on the basis of a simulated example, to be promising. In another case, adaptive deconvolution methods were quite successful.

A variety of studies continued our efforts to characterize lateral heterogeneity within the Earth. Complexities in the P-codas from some Novaya Zemlya explosions were shown to originate in a broad region which may not be associated with source or receiver region. Earlier results from a global analysis of travel-time variations were extended. It was shown that it is possible to make a convincing correlation between the inferred velocity anomalies and the gravitational field of the Earth. Another study examined the determination of *levels of velocity discontinuity* within the Earth using free oscillation data.

Other completed studies included some comparisons between various criteria that have been proposed for the determinaton of the optimum prediction error filter length for maximum-entropy spectral analysis. Also, an extension of previous work on the energy-moment tensor relation was carried out. In another investigation, the observed time series for the excitation of the Chandler motion of the Earth was compared with the calculated contribution due to large earthquakes. A good correlation was observed.

We continued to develop our data and computer systems in order to be able to handle the SRO data then on hand, and the much larger quantity of digital data soon to be available. We designed an expansion of our CONSOLE program that permits interactive display and processing of SRO data on our PDP-7 computers. Our PDP-11-based system was already operating as an ARPANET connection, and would become a general-purpose time-sharing facility in the very near future.

N. FISCAL YEAR 1977

1. October 1, 1976 to March 31, 1977

During this period, data became available from the first Seismic Research Observatories (SROs). At this time, data were being received on a routine basis from six of these stations: ANMO (Albuquerque), MAIO (Mashad), GUMO (Guam), NWAO (Australia), SNZO (New Zealand), and TATO (Taiwan). Fairly extensive data were now available for the first three of these, and we had made several first attempts to use these new data for seismological research. The quality of these data was very high, and we expected them to make a major impact on seismology as more stations became operational.

In the area of general body-wave studies, several investigations were completed. We noted the presence of small emergent phases ahead of larger, more-impulsive phases in many cases of shallow earthquakes, using the short-period SRO data. This clearly complicates the selection of onset times from conventional WWSSN film-chip data. Other studies used P-wave travel times to investigate the variation in crust and upper-mantle structure across the United States, and to determine velocities in the source region by a master-event technique. It appears possible to directly measure P- and S-wave velocity in source areas such as downgoing lithosphere slabs, and make conclusions about anomalous zones within these slabs. Earlier work on the representation of the seismic source by the moment tensor was extended to body-wave sources.

Surface-wave studies included a new rapid algorithm for the determination of group and phase velocities (Ref. 177), a series of observations of Rayleigh-wave dispersion at the Mashad SRO, and a determination of structure in the Novaya Zemlya area using a pair of events (Ref. 180). In another study, observations of NTS explosions at Albuquerque SRO were analyzed for group-velocity dispersion using a data adaptive prediction error algorithm. A study of surface-wave overtones was carried out, and a technique developed for the problem of mode separation.

A series of investigations continued our research into the determination of magnitude and yield. A study of the variation with azimuth of the LP P-wave amplitudes from two explosions showed features that were consistent with an earlier study of station magnitude bias using SP data. An initial application of SRO data to the problem of seismic scaling, and a new technique for measuring the amplitude and phase response of the determination of station-detection characteristics were developed. We were particularly concerned about the inclusion of saturation parameters, and the proper evaluation of the parameters describing seismicity. A series of stations with known parameters were then used as a model of a global network, and a synthetic earthquake catalogue for the network was generated using a simulation program. A theoretical analysis showed how the seismic energy radiated by a finite propagating line source could be evaluated using the moment-tensor formalism (Ref. 170), and a similar approach was used to calculate the explosive moments and radiated Rayleigh-wave energies for a set of U.S. explosions. In another study, the LP P-waves observed from Longshot, Milrow, and Cannikin were compared with observed SP data. It appeared that LP data may provide a much more stable measure of yield.

A wide variety of miscellaneous studies were completed. These ranged from an extension of maximum-entropy spectral analysis to the study of multichannel cross spectra, to studies of Q structure in the Earth. Cepstral analysis was applied to an event near Semipalatinsk, and it was thought to be a multiple event. The same analysis was used to detect the splitting of the pP phase due to double reflection in oceanic areas. The application of polarization filtering to LP SRO data was examined, and it appeared to be a promising technique for separating interfering phases. A theoretical development for the excitation of normal modes by a propagating fault was completed. The determination of the dissipation parameter Q is of considerable current interest. Direct measurement of Q for a number of normal modes of the Earth was outlined, and the effects of a frequency-dependent Q on velocity dispersion were being examined. A possible correlation between variations in the level of seismic activity with time and changes in the rate of rotation of the Earth was investigated.

We continued to develop our data-handling facilites. Our PDP-11 system was now a general-purpose time-sharing facility, and we were building up our applications software library for seismic research. The system allowed us to connect with the ARPANET, to larger computers, and to the datacomputer.

2. April 1 to September 30, 1977

Several investigations related to surface-wave propagation were carried out. Polarization filtering was shown to be capable of enhancing the

Rayleigh waves received at Mashhad SRO from presumed explosions in Eastern Kazakh. In particular, it was demonstrated that this technique would be valuable in separating the surface-wave trains from interfering events. A preliminary attempt to use Mashhad M_s values in application of the M_s-m_b criterion to Eurasian events was quite successful. Separation of the explosion and earthquake populations was generally good, but one presumed explosion was not identified - perhaps due to unusual tectonic strain release. We continued to improve our analysis of the crustal structure at Novaya Zemlya by comparing the data from two test sites on the island as observed at ALPA (Ref. 180). A crustal thickness of 45 km appeared to give a best fit to the data. A comparison of focal mechanisms determined by a recent surface-wave spectral amplitude fitting procedure with those obtained from LP body waves showed rather large discrepancies. Our planned experiment to carry out a large-scale inversion of Eurasian group-velocity dispersion data continued, and required data from more SRO sites soon to be operational. Data from a limited area in Southeastern Asia, as observed at Mashhad SRO, again documented the low group velocities associated with the Tibetan plateau, and indicated that these velocities persist to the north of the plateau.

We continued our efforts to understand the scaling of the seismic source and its effect on determinations of m_b. One study showed that observations of m_b vs period for the Rat Island sequence (1965) were consistent with a relatively constant stress drop of about 25 bars (Ref. 172). Estimates of seismic moment appeared to agree well with other methods. Another investigation studied the effect of the corner frequency and high-frequency fall-off in the seismic spectrum on the dominant period as observed through several SP seismograph systems. It was shown that m_b, as usually measured, is not a consistent measure of spectral amplitude at 1 Hz unless corrections for corner frequency and path attenuation are included. Information about the seismic source can also be obtained from the saturation of the m_b scale as observed in frequency-magnitude data if an earlier-derived linear relation between log(frequency) and log(moment) is assumed to be correct. Observational data appear to be consistent with a high-frequency decay of the seismic spectrum intermediate between Ω^{-2} and Ω^{-3} (Ref. 172).

Several other studies were completed. We carried out deconvolution and maximum-entropy spectral analysis of the Mashhad SRO recording of the Eastern Kazakh event of 20 March 1976. This was an unusual event, and is clearly multiple. Our best interpretation of this record suggested that at least one of the sources was an earthquake, although further data were needed to completely dispose of the possiblity that it was a sequence of explosions. We began a study of discrimination at near-regional distances by compiling a set of LRSM data from U.S. explosions. The effects of crustal inhomogeneity and the difficulty in measuring the onset times of S-phases were apparent in this data set. In another study, the application of the master-event technique to the teleseismic determination of focal depth was examined. In the study of an aftershock sequence in Iran, it was possible to determine relative epicenters and focal depths to considerable precision.

In the general areas of data analysis and computer systems, several studies were carried out. We completed a careful study of the response characteristics of the SRO instrument (Refs. 174,181). We noted that the anti-alias filter had been removed from the SP SRO system, and we recommended that attempts be made to design a new anti-alias filter. We examined the detection thresholds on the existing SRO SP systems by evaluating the detections at each station. We concluded that several of these thresholds were set too high. A new algorithm for the automatic picking of first arrivals appeared to show distinct advantages over current techniques.

We continued to upgrade the capabilities of our PDP-11 computer system. At that time, the major emphasis of our software program was aimed toward implementation of a multiple-CPU operating system, the development of a graphics package oriented specifically for seismological research, and the improvement of our interface with the datacomputer.

O. FISCAL YEAR 1978

1. October 1, 1977 to March 31, 1978

During this period, we concentrated mainly upon studying the nature of seismograms at regional distances (<2000 km) in the context of seismic discrimination. A variety of studies investigated the utility of crustal body-wave phases and SP surface waves in the detection, location, and discrimination of events at these distances.

We compared locations of three nuclear explosions in Nevada, using crustal phases only, with those from teleseismic data only and found the accuracy of the epicenters obtained to be roughly equivalent, but that crustal-phase calibration may frequently be necessary. The utility of differential Pg-Pn travel times as a depth discriminant was studied: it appears to work only at distances of less than 500 km. Crustal-phase travel-time data from NTS explosions were used to calibrate the Basin and

Range structural province. A study of film-chip recordings of Soviet explosions demonstrated that, although Pn and Sn are readily identifiable, the other crustal phases are more difficult to identify. A comparison of broad-band and SP recordings of regional events at the Albuquerque SRO seemed to indicate some advantages in broad-band recording for discrimination purposes. Two sets of sonograms, one for the western and the other for the eastern U.S., showed the viability of this technique in phase identification. Polarization filtering also appeared to enhance phase identification at regional distances.

The Lg phase was investigated for a variety of paths. Wave-number spectra at NORSAR indicated that this very emergent feature of regional seismograms is mostly incoherent and due to scattering from more coherent higher-mode Rayleigh waves of short duration. The propagation of Lg across western Russia was studied at both NORSAR and WWSSN stations in Scandinavia: it appeared to be transmitted quite efficiently across this region, with no anomalous attenuation due to either the Ural mountains or the Baltic Sea.

Amplitude-distance curves for various crustal phases were determined for eastern North America and applied to a larger dataset, including Soviet explosions, for magnitude determination. A magnitude scale based on Lg amplitudes appeared to have some utility as a discriminant when compared with body-wave magnitudes.

Several studies involving teleseismic data were also carried out. A preliminary assessment of the utility of ocean-bottom seismometers for seismic discrimination purposes was carried out (Ref. 179). The seafloor appeared likely to provide low-noise sites for surveillance of previously inaccessible regions, and recent technical developments made adequate seismometer deployment there quite feasible. A separate study of ocean-ridge earthquakes showed that their locations could be considerably improved with ray-tracing procedures in a realistic ocean-ridge model. A method for the extension of ellipticity correction to surface-reflected phases was completed. A study of P-wave velocity in the Tonga deep-earthquake zone showed a correlation of the major anomalous velocity region with sudden shear strain increase. Analysis of Mashhad SRO long-period recordings of a double explosion indicated that events separated by as little as 20 s can be identified in the surface-wave train. The spectral characteristics of events in an aftershock sequence were studied using SRO data: seismic scaling effects were readily observable.

We continued to develop our data-handling facilities. A 300-Mbyte disk greatly increased our on-line storage capability. System software, particularly that to handle datacomputer interaction, was substantially improved. The seismic display package had now been implemented.

2. April 1 to September 30, 1978

A fundamental problem in seismic-data analysis is the development of rapid automated or semiautomated methods for the routine estimation of source location and focal depth, and the association of LP data with events determined from SP arrivals. One investigation into this attempted to determine source azimuth and distance directly from surface-wave data, for comparison with SP data. With further refinement, this technique may greatly assist the association problem. Event location is primarily a problem in path calibration, and two studies addressed the application of the master-event technique. If local crustal structure is relatively simple and well known, it was shown that the addition of regional data, using travel times of crustal phases, can provide a noticeable improvement to the quality of epicenters determined from teleseismic data alone. The master-event technique could also be useful in the estimation of the relative focal depth of events. In another study, the application of seismic ray tracing to event location in a complex area was investigated.

We began a series of investigations into methods for the estimation of fault-plane solutions and the moment tensor. Two studies are concerned with the direct inversion of body-wave amplitudes to obtain the moment tensor. In the first, a case was examined in which inversion leads to a predominantly double-couple source which has an orientation rather more consistent with the tectonic environment than the published fault-plane solution. The second study attempted to estimate the potential errors introduced into the moment tensor inversion by structural inhomogeneity. Improvement to the determination of fault-plane solutions depends critically on the development of nonsubjective approaches, such as linear-estimation procedures. Another study explored the possible utilization of synthetic seismograms computed by the superposition of normal modes, and formulated the inverse problem of estimating the moment tensor from observed seismograms.

A number of miscellaneous studies were completed, consisting mainly of analysis of SRO data. Two investigations focused on the problem of event-detection algorithms. The first assessed the performance of the current SRO event detector, and demonstrated a high incidence of false alarms and disappointing performance at some stations. The second discussed some potential improvements to detection algorithms. Another study began to assess the usefulness of digital waveforms in the estimation of body-wave magnitude m_b. Station amplitude bias appears to be a significant effect, and calibration by source region may be possible. A study of mantle Love-wave dispersion began a global analysis of regional variations in phase velocity and Q. Rayleigh-wave dispersion was used to estimate the structure of the lithosphere in a remote aseismic area of the South Atlantic. Investigations of the propagation of the crustal phase Lg continued. A study showed that the observed phase velocities of the vertical component of Lg are consistent with the expected behavior of higher-mode Rayleigh waves.

We continued to make improvements to our in-house computer system, and focused our programming effort into those areas that will have eventual application in a global treaty monitoring context. A new version of our Data Analysis and Display System (DADS) was installed, together with improvements in our waveform graphics package and the speed of display of waveforms on our storage display terminals. We were currently retrieving SRO data from the datacomputer, and were developing software for this purpose. We were reducing the size of our library collection of digital seismic data so that proper tape maintenance could be instituted.

P. FISCAL YEAR 1979

1. October 1, 1978 to March 31, 1979

The Lincoln Laboratory program during FY 79 had two objectives. The first was to carry out a detailed design study, and produce hardware and software specifications for a Data Center which will fulfill U.S. obligations that may be incurred under the Comprehensive Test Ban Treaty, and under any international agreements that may be associated with this treaty. The second was to carry out seismic research, with particular emphasis on those areas directly related to the operations of the Data Center.

We made a final attempt to formulate the functions of the Data Center. Both alphanumeric and waveform data, some in real time, will be transmitted to the Data Center. The main products of the Data Center will be one or more event lists, an archive for all the input data, and a set of event-associated waveform files which will be useful for research and development. The architecture of the Center was being formulated using state-of-the-art computer technology, and would be described in detail in a special report to be issued late in FY 79. For the present, we focused on Center requirements using current estimates of data-flow rates, and we were exploring some important interface issues that are yet to be completely resolved. Seismicity variations are substantial, and may at times place a severe load on the processing capability of the Center. The average number of events detected per day, including local events, is likely to lie in the range 50 to 100. It has been shown that episodes of 2 or 3 times this activity are relatively common. We were also concerned about the process of event detection, and a study compared the computational load generated by a variety of detection algorithms. Research into the effectiveness of these algorithms continued.

One of the major tasks of the Data Center would be to locate seismic events. A number of studies related to this task were completed. Two investigations applied the master-event technique - one to the improvement in epicenter accuracy that can be obtained using regional data, and the other to the improvement in focal-depth resolution that is possible. An attempt to improve the regionalization of Rayleigh-wave travel times was carried out, including an extensive review of station travel-time anomalies. Using the ISC Catalog for 1964-75, a new set of travel-time anomalies was prepared for 751 stations. These anomalies included both first- and second-order terms in azimuth, as well as a zeroth-order term. The tables constituted the most comprehensive data on station travel-time anomalies currently available.

Several other studies were completed. Amplitude spectra of crustal phases observed from an earthquake in eastern Canada at a distance of 5° showed substantial signal at frequencies as high as 30 Hz. Observed Q values for each of the crustal phases were very high. In another study, the dispersion of mantle Love waves was completed. Lateral variations in structure beneath continents and oceans below about 200 km were not required by the data. We carried out an analysis of broadband SRO data, and suggested transfer functions for instruments designed for seismic monitoring at regional distances.

We continued to develop the capabilities of our in-house PDP-11 computer system. Much of the software used on this system would have application in the Data Center.

2. April 1 to September 30, 1979

The preliminary design stages for the SDC were now completed. A document detailing the objectives, requirements, and design philosophy of such a Center was completed and submitted as a special internal report to the Nuclear Monitoring Research Office of the Defense Advanced Research Projects

Agency (Ref. 188). We made progress in the automation of some functions such as magnitude determination to assist analyst operations.

We continued our analysis of data produced by the network of Seismic Research Observatories (SROs), the installation of which is nearing completion. The network then consisted of 17 digitally recording stations and provided fairly good global capability for detection, discrimination, and source mechanism determination. Three studies using SRO data were completed. The actual network detection capability for the network of 12 stations operating during January to July 1978 was determined and shown to fall only slightly short of that predicted from individual station detection characteristics. A discrimination experiment for Eurasian events showed network complexity averages to be a surprisingly good discriminant. It was shown that the current response characteristics of the long-period SRO data channels severely limit the network's capability to carry out the simplest method of source mechanism determination, that of fault-plane solutions.

We carried out three studies in the field of general seismology. We continued our interest in regional seismology and attempted to quantify the apparent anelastic properties of the lithosphere in eastern North America using data from the Eastern Canada Telemetered Network. The ratio of shear-to-compressional attenuation was shown to be close to unity from spectra of local events, compared with approximately four from teleseismic signals. Previously described attempts to estimate the moment tensor from LP body waves were developed further, and double-couple components of this tensor between 71 and 85 percent were obtained for three events in greatly different seismic regions (Ref. 190). A method for constructing synthetic seismograms when only the amplitude spectrum of the reduced velocity potential is known was applied to the Salmon nuclear explosion using the assumption of minimum phase.

Q. FISCAL YEAR 1980

1. October 1, 1979 to March 31, 1980

During FY 79, Lincoln Laboratory completed a design for a state-of-the-art SDC, and the FY 80 program consisted of beginning the actual development of such a Data Center, and carrying out seismic research with special emphasis on those areas directly related to the operations of the SDC.

The Lincoln program focused on the development of three subsystems of the SDC - namely the Seismic Analysis Station (SAS), the Local Computer Network (LCN), and the Data Base Management System (DBMS). Initial work was focused heavily on the SAS and, in particular, on a pre-prototype software system referred to as Mod I. This system, running on our in-house PDP-11/45 computer, would allow experimentation and the development of new-generation techniques for seismic-data analysis and event bulletin preparation, that would be implemented on the SAS hardware later in the current fiscal year.

The DBMS and the LCN were in the design and procurement phases. The DBMS design was refined substantially from that described in the SDC Design report, and now included a more comprehensive discussion of the indexing of waveform data for rapid retrieval. The LCN requirements were formulated in detail, and were being procured.

We began to examine the seismic algorithms that would be employed in the SDC. Automatic association and location algorithms were selected for implementation in the Mod I system. As experience in the use of this system grew, we expected to improve or replace these algorithms with better ones. We continued our interest in detection algorithms, and developed an algorithm that is more sensitive to emergent arrivals. A synthetic program to generate both artificial seismicity and arrivals at a prescribed set of stations was written. This would be used to test and evaluate SDC algorithms.

A major emphasis of the seismic research program was in the area of source characterization using the moment-tensor formulation. Attempts were made to understand the generation of anomalous Rayleigh waves by certain explosions at the Eastern Kazakh test site. It was shown that certain components of the moment tensor were very poorly resolved for events with zero depth. Analysis of the anomalous events strongly suggests that they were accompanied by faulting. A new method for the simultaneous inversion of surface-wave data for both moment-tensor and source location was formulated. This method showed considerable promise for the analysis of special events.

We continued to develop our in-house computer systems. New enhancements to the UNIX operating system, a new graphics package, and the installation of UNIX-compatible FORTRAN 77 were completed.

2. April 1 to September 30, 1980

Until this time, the Lincoln Laboratory program had focused on three of the most important subsystems of the prototype SDC: the SAS, the LCN, and the DBMS. Hardware acquisition for the SAS was essentially completed, and efforts in this area were focused on the development of a responsive waveform display which would include a smooth scrolling capability. Hardware for the prototype DBMS was on order, but had not yet been received. Efforts in this area concentrated on the development of a modification to the kernel of the UNIX operating system that will permit rapid data transfer. The modified system, TUNE, was nearing completion and would possibly be utilized in the SAS. The LCN was being developed to our specifications by a subcontractor.

Research into the algorithms that will form the basis for seismic processing at the SDC continued in several areas. On the basis of their spectral characteristics, it appeared possible to identify local signals automatically with a high degree of success. A set of synthetic arrivals was used to evaluate some existing automatic association algorithms. There was a substantial gap between the performance of these algorithms and the much better performance of a human analyst, but future research was expected to reduce this difference. Evidence was obtained that it may be necessary to routinely use master-event techniques for earthquake location in regions of strong lateral inhomogeneity, such as island areas. We examined some of the difficulties involved in the identification of SP depth phases, and showed that useful information could be obtained from LP body-wave records when they are available.

Research in general seismology included a study of the anomalous Rayleigh waves emitted by certain events at the Eastern Kazakh test site. The characteristics of these surface waves could be explained on the basis of a combined explosion/thrust faulting mechanism (Ref. 204). A series of investigations used mantle waves of long period, and results using both synthetic and real data showed distinct promise. Involved in this study (and many others) was the computation of an average path-dispersion characteristic for a surface-wave path that traverses several different provinces. Analysis of this problem showed that computation of this path average, at least in certain cases, should not be based on simple geometrical path lengths in each region, but should use some additional parameters which may be computed.

R. FISCAL YEAR 1981

1. October 1, 1980 to March 31, 1981

Substantial progress was made in the development of the first version of the prototype SDC. In the absence of a LCN, which was expected to be delivered during the next quarter, the SAS and data-base subsystems were being developed as stand-alone systems. Seismic processing techniques were being developed on our general-purpose computers. We demonstrated the capability to read input seismic data, carry out signal detection and the automatic extraction of a variety of signal parameters, and display the detected waveforms for analyst review. A variety of additional analyst software tools would be installed soon on the SAS. The waveform and parameter data-base systems were being developed on the SAS as local facilities, and they would be expanded to system-wide data bases at a later stage. A Remote Seismic Terminal, capable of limited waveform display and analysis and remote interaction with the SDC over dial-up line, was demonstrated.

An important effort during this period was the development and implementation of a variety of seismic processing algorithms for automatic signal analysis, and analyst interactive review. A package of programs for automatic analysis of incoming data was installed on our VAX 11/780 computer. These included programs for signal detection, onset time measurement, and discrimination between local and teleseismic events. In the prototype SDC, provision was made for analyst review and modification of each of these measurements. The output sets of arrival parameters were then merged with any external arrival data into a local parameter data base. This was followed by automatic association into a preliminary event list, analyst review of the output using available waveform data, and final event bulletin preparation. We continued to evaluate and develop a series of additional algorithms for phase identification, azimuth measurement, and association of LP arrivals with events determined from SP data.

Other seismological research continued in several areas. Previous work on anomalous surface-wave excitation by presumed explosions in the Eastern Kazakh region was extended (Ref. 204). A variety of evidence was found in support of the hypothesis that thrust faulting accompanies these unusual events, and that at least some observed tectonic strain release by Nevada Test Site events can also be attributed to this type of faulting (Ref. 204). Other studies included: an inversion of Rayleigh-wave phase and group mantle structure in the Middle East and South Central Asia; a method for the evaluation of mode eigenfunctions for P and SV motion in a layered medium, which is numerically stable; and an application of this technique to the study of the excitation of the Lg phase as a function of source depth. A generalization of the method of centroid location to the estimation of source parameters (particulary moment and hypocenter) for events close in time was formulated and applied to the resolution of explosion and earthquake sources, and to the modeling of finite seismic sources. In another investigation, the effect of a boundary on the radiation from seismic sources was evaluated, with particular emphasis on contributions to the moment tensor. It was shown that assumptions about the boundary are necessary if a proper interpretation of the moment tensor is to be obtained. The application of finite difference methods to the calculation of normal-mode eigenfrequencies and eigenfunctions so that seismogram synthesis may be performed at higher frequencies was investigated.

2. April 1 to September 30, 1981

During this period, the first working prototype SDC was completed. This system was capable of accepting input of both parameter and continuous waveform data, carrying out automatic signal detection and parameter extraction on the waveform data, merging all parameters, and carrying out automatic association to produce an event list. Review by a human analyst was provided for, both after automatic signal processing and after automatic association. Analyst interaction utilized a single-user interactive computer graphics system called the Seismic Analysis Station (SAS). This prototype would form the basis for future SDC development.

Several studies in the area of Seismic Processing were carried out. One study demonstrated that augmented transition network (ATN) grammars could be of significant use in the recognition of glitch noise. Another compared ATN grammars with dynamic time warping as means for the recognition and characterization of seismic signals. A third study described the affinity technique for the analysis of the morphological structure and information content of seismic signals. We began to apply the concepts of expert systems to the problem of automatic association (AA), and expected that this would lead to much more intelligent AA programs (Ref. 205). Another investigation examined the use of hash functions, and the application of entropy concepts to measure their performance. These functions may have an important application to the retrieval of information from data-base storage. We began to study potential improvements in signal detection. It was shown that the number of significant detections obtained in a given time period can be increased by carrying out signal detection on the horizontal components of 3-component instruments. We also completed an extensive comparison of the performance of automatic techniques and the human analyst in picking the first arrivals of seismic signals. While the automatic methods produced more false alarms, they were comparable to the analyst in detecting real signals. Analysts were shown to be less reliable than commonly assumed.

Several studies in general seismological research were completed. A detailed review of frequency-dependent anelasticity was carried out. Additional evidence for absorption-band models was obtained. Another study approached the problem of including transverse isotropy in ray theoretic calculations. Several new extensions of a method, developed earlier, for the simultaneous estimation of seismic moment tensor and event hypocenter were completed. Application of these methods to several recent earthquakes was carried out. In one case, evidence was found that a complex series of motions occurred at the seismic source. Finally, an application of a new method for the analysis of mantle waves showed how these can be used to extract direct information on Earth structure.

S. FISCAL YEAR 1982

1. October 1, 1981 to March 31, 1982

A prototype SDC was completed in FY 81. The Lincoln Laboratory FY 82 program consisted of refining and improving this prototype, and transferring it to its operational site in Rosslyn, Virginia.

During this period, the prototype SDC was demonstrated to DARPA and accepted as the basis of an operational system. Substantial improvements were made to the SAS, leading to a much more flexible and useful user interface. The data-base management system INGRES, developed by Lawrence Berkeley Laboratory, was installed and tested in the prototype SDC. Attempts were made to accelerate certain types of data retrieval from this system. The Communications Interface Subsystem (CIS) was being assembled under subcontract by Teledyne-Geotech. A first shipment of computer equipment to the Virginia site was completed, and a detailed schedule was prepared for the shipment of all remaining equipment during the second half of FY 82.

Several studies were completed. A special experiment to test the communication facilities of the WMO/GTS was completed during November and December 1981. Substantial discrepancies were observed in the event bulletins prepared in Sweden and the U.S. using the same data set. A detailed report on these discrepancies was prepared. In another area, an English-language interface was constructed to permit easy interaction with the list of seismic events stored in the data-base management system. Further extensions of this concept could make the seismic data in the SDC much more accessible to noncomputer specialists.

An investigation in the area of yield estimation research was being carried out under subcontract at M.I.T. The initial portion of this study focused on the trade-offs between explosion source parameters and anelasticity. It was shown that some ambiguity in interpretation arises from these trade-offs, due in large part to the difficulty in modeling the pP phase (Ref. 206).

2. April 1 to September 30, 1982

During this period, Lincoln Laboratory continued the transfer of technology to the new Center for Seismic Studies (CSS) in Rosslyn, Virginia, and participated in a demonstration of the SDC facilities at that site.

The remainder of the period was occupied with completing the transfer of all remaining equipment to the CSS, and phasing out the VELA UNIFORM project at Lincoln Laboratory by the end of FY 82.

III. SEISMIC DATA CENTER IMPLEMENTATION

A. DEPARTURES FROM THE ORIGINAL LINCOLN LABORATORY DESIGN

A document entitled "Design of a Seismic Data Center" was submitted as a special internal report to DARPA in September 1979. This was in response to a DARPA request to formulate the design of an entirely new state-of-the-art system that would be capable of fulfilling whatever requirements might be specified in the Comprehensive Test Ban Treaty (CTBT). These requirements could, in the absence of such a treaty, be only tentatively estimated, but flexibility and reliability were clearly major considerations. The data load on the system was determined mainly by an estimate of about 30 stations producing real-time continuous multiple-band and multiple-component seismic data. The design as specified in the report was centered on a hardware configuration consisting of multiple minicomputers interconnected by a local computer network, permitting flexible response to changing requirements. Reliability was to be accomplished by including redundant machines for crucial functions.

At the time of design completion there was no need for a full-scale implementation of the entire system as proposed. Lincoln Laboratory was therefore asked to assume the task of constructing a prototype system capable of testing the design concepts. This prototype differed in several important respects from the overall design, as outlined below. To some extent these differences were dictated by rapid changes in both the availability and cost of hardware, as well as two new DARPA motivations for the SDC project. The first of these was increased U.S. participation in international experiments proposed by the Group of Scientific Experts of the Committee on Disarmament and the consequent need for a single facility prepared to coordinate and carry out such tasks. The second need concerned the establishment of a centralized repository capable of constructing and making available data sets to be used in special experiments in areas of interest to DARPA, as well as specialized software developed under DARPA contracts.

1. Hardware Differences

The original design called for several reliable computer modules consisting of two DEC 11/44 computers with multiple-access peripherals, each working on part of the same task. This was predicated by the need for reliable capture of the incoming data. Such a configuration is maintained only for the communications interface subsystem (CIS), which will shortly consist of two 11/44 computers, one mainly dedicated to receipt of the incoming RSTN data and the other to the less urgent data such as SRO tapes and WMO parameter input. Provision has been made for transfer of RSTN data collection to the second machine should the first fail, in which case SRO tape input would temporarily be interrupted. WMO input can also be achieved using either machine.

The increasing availability and falling cost of 32-bit computers since the original design completion in 1979 has to some extent made the original PDP-11-based system obsolete. The Seismic Analysis Station was moved from an 11/44 to a VAX 11/780 late in FY 82, wi considerable improvements resulting in both speed and ease of programming. The limited address space of the 11/44 had imposed severe constraints upon the implementation of the waveform graphics.

The current configuration has two DEC VAX 11/780 computers, one performing the general computational support as envisioned in the original design and the other carrying out the data-base functions. These larger machines are considerably more powerful than the originally specified computers and can each readily assume several functions which were distributed over two or more machines in the original design. Adequate backup of incoming data is provided by the CIS.

The prototype design called for using a local computer network (LCN) to to interconnect all the machines. T e LCN was subcontracted to Sytek, Inc. In the meantime, a limited alternative was implemented based on DEC DMR-11 high-speed serial controllers. These DMR interfaces are about to be replaced by a ring-type network which has been ordered from Proteon, Inc.

2. Functional Differences

In addition to the differences caused by the changed hardware configuration, there are some major changes in the area of data bases. The original design included a parameter data base to be tailored to the seismic data collection, processing, and archival requirements for the SDC. The waveform data were to be handled by a separate but linked data-base system which was organized to handle the large data flows and reliable archive requirements which are anticipated in the treaty environment.

The prototype as implemented in the CSS has all the data-management functions centralized on a VAX using INGRES, a relational data base management system (DBMS) developed at UC Berkeley. The parameter data are stored directly in numerous tables in a data base implemented by INGRES. The waveform data are stored in files whose names are stored in appropriate entries in the tables of the INGRES data base. The use of INGRES gives a great deal of flexibility and provides a powerful query facility at the expense of speed of response. The added flexibility is an advantage in the more researcher-oriented multipurpose uses now envisioned for the SDC, but the response time continues to be a matter for concern, primarily in keeping up with the incoming RSTN data.

B. DIRECTIONS FOR FUTURE DEVELOPMENT

Although, as described above, the present implemention of the SDC as the Center for Seismic Studies in Arlington, Virginia differs in some important respects from the original design, the flexibility afforded by the multiple-computer configuration has proved to be a considerable asset in satisfying changing DARPA requirements for the overall system. Increased involvement in international data-exchange experiments, together with the accommodation of a rapidly increasing number of visiting researchers, is quite feasible with the system as it exists at present. Adding these new objectives while still satisfying many of the functions originally envisaged for the SDC - the most important of which is the reception, indexing, and archiving of the real-time data produced by the RSTN stations - is not a simple task.

1. Data Management Systems

A current concern of users is the responsiveness of the INGRES DBMS. As a generalized relational DBMS, INGRES provides much flexibility and power which are not always applicable to the seismic data-management problem. From the research user's point of view, the flexibility of such a relational DBMS is a major asset for the use of which he may well be willing to sacrifice immediate response. In dealing with continuously arriving real-time data, this same flexibility is a liability in that it degrades the ability to keep up with the incoming data stream. A major, and still unanswered, question is whether INGRES can be made sufficiently responsive for the operational aspects of the CSS. Tests are now in progress to attempt to answer this question. These tests may well indicate that a specialized DBMS must be implemented for real-time data collection purposes.

2. Reliability

The reliable capture and archiving of the received data are highly desirable goals of the CSS. The present implementation does not use the reliable computer configuration featured in the original design. The hardware (an additional PDP-11/44) necessary to achieve this for at least the Communications Interface Subsystem has just been shipped to the CSS and should be added to the current system to ensure that at least the data collection is uninterrupted by the failure of a single machine. Tape backup is presently provided by CIS in case of failure of the data storage and archive processes which now take place on a single VAX.

3. Integration

The integration of the subsystems in the SDC was a long-term goal of the design, which was predicated on the use of a local computer network to tie together the computers supporting the subsystems of the SDC. The subcontractor for implementation of the LCN (Sytek, Inc.) is behind schedule and continuing to experience problems in developing a final product. For the present, the machines in the prototype are interconnected by DEC DMR-11 high-speed serial links, which do not possess the required level of connectivity between computers. A low-cost ring-type network has just been purchased from Proteon, Inc., and will be installed for testing as an alternative to the Sytek LCN.

Once the LCN (either Sytek or an alternative) is working, system-wide monitoring should be implemented under the control of a single system operator. The next step would then be the development of an integrated system-wide file system which would allow applications programs on any given machine to use files on any other, obviating the need to copy data from machine to machine, which creates potential problems of data consistency and, of course, wastes on-line storage space.

The final step in integration would be a fully integrated system-wide operating system which would allow a user on any available machine to access not only data, but also computational resources, on any machine without specifying the site. This allows the maximum utilization of the system-wide resources and allows for automatic control and reconfiguration to promote reliability and responsiveness for all users an. processes.

4. Hardware

The Communications Interface Subsystem is presently implemented on two PDP-11/44 computers. The limited address space of these 16-bit machines has severely hampered software development and caused bottlenecks in routine processing. The replacement of these computers by small 32-bit VAXs is strongly recommended. This would have the added advantage that the same version of the UNIX operating system could be implemented on each machine and ensure full software compatibility if it becomes necessary to redistribute the total load between computers.

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GLOSSARY

AA	Automatic Association
AFTAC	Air Force Tactical Applications Center
ALPA	Alaskan Long-Period Array
ARPANET	DARPA Computer Network
ATN	Augmented Transition Network
BBC	British Broadcasting Corporation
CIS	Communications Interface Subsystem
CPO	Cumberland Plateau Observatory
CPU	Control and Processing Unit
CSS	Center for Seismic Studies
DADS	Data Analysis and Display System
DARPA	Defense Advanced Research Projects Agency
DBMS	Data Base Management System
DC	Zero Frequency
DEC	Digital Equipment Corporation
GTS	Global Telecommunications System
IBM	International Business Machines
ISC	International Seismological Center
ISM	International Seismic Month
kt	Kiloton
LASA	Large-Aperture Seismic Array
LCN	Local Computer Network
LP	Long Period
LRSM	Long-Range Seismic Measurements

m_b	Body-Wave Magnitude
Mbyte	Megabyte
M.I.T.	Massachusetts Institute of Technology
M_s	Surface-Wave Magnitude
Mt	Megaton
NLS	On-Line System
NMRO	Nuclear Monitoring Research Office
NORSAR	Norwegian Array
NTS	Nevada Test Site
rms	Root Mean Square
RSTN	Regional Seismic Test Network
SAS	Seismic Analysis Station
SATS	Semiannual Technical Summary
SDAC	Seismic Data Analysis Center
SDC	Seismic Data Center
SNR	Signal-to-Noise Ratio
SP	Short Period
SRO	Seismic Research Observatory
TFO	Tonto Forest Observatory
t*	Attenuation Parameter
UC	University of California
UN	United Nations
VESPA	Velocity Spectral Analysis
WMO	World Meteorological Organization
WWSSN	World-Wide Standard Seismograph Network

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This is the Final Report on the Lincoln Laboratory Vela Uniform program. Section I presents an overview of the program from its beginning; summaries of our technical accomplishments for the Fiscal Years 1964 through 1982 are presented in Sec. II. The implementation of the Seismic Data Center is described in Sec. III. A list of publications relevant to our research is supplied in Sec. IV.